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SYSTEMATIC INVESTMENT IN CAPITAL AND LOGISTICS FOR UNEXPLODED ORDNANCE PLANNING STUDY (SICLUPS)

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The Center for Army Analysis developed and demonstrated a methodology for determining optimal ways to schedule and allocate funding for the clean-up of unexploded ordnance (UXO) on a large number of formerly used defense sites (FUDS), where optimality is defined in terms of Army goals, including health, safety, and environmental protection. The methodology involves formulating and solving a mixed-integer linear programming (MIP) problem. Analyses of solutions of the MIP problem are presented, showing that the SICLUPS methodology provides the sponsor with a range of choices about which Army UXO goals to emphasize in determining the schedule. It should be possible to apply the methodology to make objective decisions as to how to divide funds for clean-ups among the various Corps of Engineers divisions and districts.

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SYSTEMATIC INVESTMENT IN CAPITAL AND LOGISTICS FOR UNEXPLODED ORDNANCE PLANNING STUDY (SICLUPS)

SUMMARY

THE PROJECT PURPOSE was to determine optimal ways to schedule and allocate funding for the clean-up of unexploded ordnance (UXO) on a large number of former Department of Defense (DoD) ranges, where optimality is in terms of Army goals, to include health, safety, and environmental protection.

THE PROJECT SPONSOR was the Assistant Chief of Staff for Installation Management (ACSIM-ODEP).

THE PROJECT OBJECTIVES were to:

(1) Determine optimal site remediation schedules, for several criteria of optimality.

(2) Compare different optimization results arising from different criteria of optimality, and perform trade-off analyses with these results for different Army UXO program goals.

(3) Objectively determine how to divide funding for UXO clean-ups of former DoD ranges among the various Corps of Engineers divisions and among the districts within the divisions.

THE SCOPE OF THE PROJECT is limited to the clean-up of UXO on 126 Formerly Used Defense Sites (FUDS), under the Defense Environmental Restoration Program (DERP). Chemical and radiological contaminants are not considered. Bases that are still DoD property are not considered in this project.

THE MAIN ASSUMPTION is that remediation of each site consists of 3 phases, which are always carried out in the same order, without repetition or backtracking. In reality, UXO remediation is a process with which the Army has had only limited experience, and the regulations that will specify the steps of remediation in detail are still being written.

THE PRINCIPAL FINDINGS are that there are multiple ways of scheduling the site remediations; that applying the SICLUPS methodology with different weighted combinations of Army UXO goals leads to different schedules, with different results, in terms of numbers of acres cleared, numbers of acres cleared in high-population areas, and numbers of acres cleared per million dollars spent. The methodology developed provides a basis for deciding objectively how to divide funding among several Corps of Engineers divisions and districts.

THE PRINCIPAL RECOMMENDATIONS are:

(1) that the Army use the methodology developed in this project to determine remediation schedules for UXO clearance on formerly used defense sites throughout the continental U.S.

(2) that the Army use the methodology developed in this project to decide objectively how to divide funding for UXO clean-ups among the various Corps of Engineers divisions and districts

(3) that the Army Environmental Center make further efforts to improve cost estimates of site clean-ups.

THE PROJECT EFFORT was conducted by David S. Anker, Resource Analysis Division, Center for Army Analysis.

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1 INTRODUCTION

1.1 Background

As a result of decades of training and weapons testing on present and past Department of Defense ranges, unexploded ordnance (UXO) and other contaminants have accumulated. This situation poses safety, health, and environmental hazards. This problem applies not only to sites presently under Department of Defense (DoD) control, but also to sites that have been transferred out of DoD control. These sites are referred to as Formerly Used Defense Sites (FUDS). As an increasing population in the continental United States puts ever more land to non-military uses, there is an increasing tendency for FUDS in particular to be put to non-military uses. When this occurs, the problem of danger to people from accidental detonation of unexploded ordnance becomes particularly acute. There is also the danger of contamination of soil and water by explosive materials and other contaminants that have leaked out of unexploded ordnance.

The UXO problem applies to ranges from all of the armed services, but, as far as land ranges are concerned, the greatest portion belongs to the Army. This is the case, whether the Army's portion is measured by (1) the number of ranges, (2) the acreage on the ranges, or (3) the preliminary estimates of the costs of clean-up of UXO.

The U.S. Army Corps of Engineers (USACE) has primary responsibility for planning and overseeing UXO clean-ups. The Environmental Division of USACE currently has 9 environmental programs. These include the Defense Environmental Restoration Program (DERP) for FUDS (DERP-FUDS), the Base Realignment and Closure (BRAC) Environmental Restoration (ER) for BRAC sites, and the Army Installation Restoration Program (Army IRP) for active sites.

The DERP-FUDS program is a large one, with over 9000 potentially contaminated properties, with a FUDS project expected to take anywhere from 2 to 10 years to complete. In this program, there are 3 categories of projects:

(1) hazardous, toxic, and radioactive waste (HTRW)

(2) building demolition and/or debris removal

(3) ordnance and explosive waste.

The 3rd category includes removal of ordnance and explosive waste (UXO) and removal or remediation of explosive-contaminated soil and chemical warfare materials.

This study pertains to this 3rd category of the DERP-FUDS program. There are legal and regulatory bases for deciding what actions will be taken according to what procedures. At the time of this writing, regulatory issues are still being worked out. Within the legal and regulatory framework, USACE has responsibility for establishing and carrying out the remediation process.

In this report, the words "remediation" and "clean-up" will be used interchangeably to denote UXO removal under the DERP-FUDS program.

The Army Environmental Center, located at Aberdeen Proving Ground, is conducting the Army's Range Inventory program, a comprehensive effort to collect range data, as required by

internal DoD directives and Congressional mandates. This program has 3 phases, of which the 3rd pertains to FUDS, among other sites. USACE is the primary executor for the 3rd phase, which involves evaluating over 1300 properties. This inventory began in 2000 and is expected to continue through 2003.

The Office of the Director of Environmental Programs (ODEP) and AEC are developing a Strategic Plan for Environmental Support to Ranges and Munitions to provide environmental support for 3 key goals, of which the 3rd is, as stated on the USACE website, "to respond to military munitions, including unexploded ordnance .... and perform the required response actions necessary to protect public health, safety, and the environment".

1.2 Purposes

The purposes are:

(1) to determine optimal site remediation schedules for a 36-year time period, for several criteria of optimality

(2) to address a number of Army UXO planning goals, including:

- **(a)** maximizing the number of acres remediated
- **(b)** maximizing the number of acres remediated per million dollars spent
- **(c)** maximizing the number of people for whom risk of injury is reduced
- **(d)** minimizing the expected severity of injury due to detonation of UXO on one of the sites, if such an injury occurs
- **(e)** minimizing the length of time taken to remediate higher-risk sites
- **(f)** minimizing the cost of remediation of a given set of sites
- **(g)** combinations of two or more of the above goals

(3) to provide a basis for deciding objectively how to divide the available funding among the various divisions and districts.

Optimality is defined in terms of risk reduction and land reuse. Army UXO planning goals are addressed by using one or a combination of these goals in defining each criterion of optimality.

Computing times should be short enough so that it is practical to apply the methodology repeatedly to obtain several schedules, and to compare results.

1.3 Key Assumptions

The key assumptions for this project are as follows:

(1) The time-line for completion of remediation is assumed to be a 36-year period. This assumption was made because it was found that a period of a few decades was needed to achieve remediation of a reasonable number of sites, and computational and other considerations for the optimization demanded a grouping of years into longer time periods. The longer time periods were chosen to be 6 years long, with the result that the duration of the whole time-line had to be a multiple of 6 years.

(2) The 3 phases of remediation of any site are always carried out in the specified order, without any backtracking or repetitions. It was necessary to make this assumption to formulate the optimization problem in the appropriate mathematical framework.

(3) The cost of the remedial design phase of remediation of a site is 0.1 times the cost of the study phase. This assumption was made because the estimate given in AEC's file of cost estimates was considered unrealistic. The cost estimates for remedial design given there were the same $50K for all sites, which seemed inconsistent with the widely accepted notion that costs vary greatly with the size and complexity of the site. The formula chosen for the cost of the remedial design phase was the best guess we could make on the basis of the limited information available.

(4) Remediation of a site is complete by the end of the 6-year time segment in which the cumulative funding for it has equaled the estimated cost. It was necessary to have a way of determining when remediation of a site is actually complete, so that the optimization model can assign a value to the remediation. This assumption gives a way to make this determination and also to allow for the possibility of a short delay between the allocation of funds for a task and the task's completion.

(5) At most 2 of the 3 phases of remediation of a site can be carried out within a given 6-year time segment. This assumption is based on information we obtained about lengths of time that are typically needed for the 1st and 3rd phases: it is not unusual for these times to be 6 years or longer.

In the remainder of this report, the term "time segment" refers to one of the 6-year time periods into which the 36-year time-line for remediation has been partitioned.

1.4 Key limitations

The key limitations for this project pertain to the data and are as follows:

(1) The cost estimates are the expected costs, each of which is a point in an interval of possible costs given by AEC, ranging from the "best case" (lowest) cost to the "worst

case" (highest) cost. This interval of uncertainty is often wide, with the "worst case" cost being over 3 times the expected cost in some cases.

(2) Risk scores, pertaining to risk of injury from UXO, are available for only some sites.

(3) Future costs and future risk due to (a) discovery of more UXO on sites and (b) future development in the vicinity of sites are difficult to project decades into the future. Future costs and future risks will impact the optimal schedule, because the amount of remediation that can be done is affected by costs, and, in the optimization model, the value of a site remediation depends on the risk associated with UXO on the site.

1.5 Scope

The scope of this project includes 126 sites: 26 sites in Florida and 100 sites in California. Of the 100 sites in California, 80 were in the Los Angeles District of the USACE and 20 were in the San Francisco (SF) and Sacramento (SAC) Districts of the USACE. The 3 main geographic areas, 3 sub-areas of each main geographic area, and the counties in the sub-areas that contain sites in the model are listed in Figure 1.

We chose to concentrate the study on sites in the states of Florida and California, because USACE appeared to have made the greatest efforts in maintaining up-do-date risk data for these two states. For the SICLUPS model, we chose, among the sites in the DERP-FUDS program for UXO that are located in these two states, those for which complete cost estimates were available.

Florida	BEACH: Nassau Monroe Duval Charlotte St. Johns Sarasota Volusia Manatee Indian River Pinellas St. Lucie	INTERIOR: Highlands Orange Clay Marion Baker De Soto Lake Putnam	ORLANDO: Orange
SF and SAC Districts	NORTH: Humboldt Siskiyou Modoc Lassen	SOUTH: Monterey Stanislaus Merced Fresno	BAY AREA: Marin Sonoma Yolo
Los Angeles District	COAST HIGH POPULATION: Orange San Diego Los Angeles	COAST LOW POPULATION: Ventura Santa Barbara	INLAND: San Bernardino Riverside Imperial

Figure 1. Counties comprising the 3 sub-areas of each of 3 main geographic areas for basic model

1.6 General Methodology

The general methodology for this project can be divided into four phases:

(1) Collect data.

(2) Run the SICLUPS optimization program to solve for the schedule that maximizes the total value of site remediations – this is a schedule at the time segment level.

(3) Run the post-processing program to obtain properties of the solution obtained in step **(2)** that pertain to Army UXO program goals, both generally and for specific geographic areas.

(4) Refine the schedule at the time segment level to a schedule at the year-by-year level.

The Army Environmental Center (AEC) provided cost estimates and acreage data for all sites in the model. The U. S. Army Corps of Engineers (USACE) provided risk data for some of the sites. Acreage and risk data for the individual sites in the model are given in Appendix L. The

cost estimates are not shown because the sponsor who provided them requested that they not be published.

The SICLUPS optimization program, which uses mixed-integer linear programming (MIP) to find an optimal schedule for the basic model, is discussed in Chapter 3. The optimization program determines for which time segment(s) a phase of a site remediation is scheduled, but not for which specific year within the time segment it is scheduled. The output of the SICLUPS optimization program is input to the post-processing program. How to choose values for weighting factors in the model on the basis of Army UXO program goals, and how to do post-processing to study how well the solution achieves these goals are covered in Chapter 4. Post-processing results for a case study are also presented in Chapter 4. Finally, refinement of the schedule at the time segment level to a schedule at the year-by-year level is discussed in Chapter 5.

Details of the output of the two computer programs are described in Appendices H and I; reasons for the grouping of years into time segments in the MIP model and some options for refinement of the schedule to the year-by-year level are described in Appendix K; and computing times of test runs of the optimization programs for the basic model and for some modifications of this model are discussed in Appendix G.

2 DEFINITIONS

2.1 The Risk Assessment Code (RAC)

The Risk Assessment Code (RAC) is a score that is assigned to individual sites, developed and applied by USACE. The RAC score of a site is intended to be a measure of the risk of injury to people due to accidental detonation of UXO on that site. This score applies particularly to some types of ordnance that may detonate simply by being touched, moved, or picked up. The RAC score is a number 1, 2, 3, 4, or 5, with 1 representing highest risk and 5 representing lowest risk. The RAC score is computed from a combination of the following two quantities:

(1) Hazard severity – an indicator of the expected severity of an injury to a person while on the site, and
(2) Hazard probability – an indicator of the probability that people will suffer such injuries.

The hazard severity and the hazard probability of a site are computed from various data pertaining to UXO discovered on the site and development in the vicinity of the site. Since there is the strong possibility of undiscovered UXO on a site, the condition that a site has a RAC score of 5 does *not* mean that the site is free of risk.

2.2 How are risk and risk reduction measured in SICLUPS?

In examining the RAC scoring process, we noted that in the computation of the hazard probability, data on development in the vicinity of the site at distances greater than 5 miles from the site boundary were not used. Since we judged that density of people living at greater distances was relevant to the risk of injury, we augmented the RAC score to measure risk in SICLUPS. Risk for a given site is considered to depend on (1) the site's RAC score and, in addition, (2) an indicator of the population of a region containing the site. This region is either (a) the county C containing the site or (b) the larger region consisting of C and all counties adjacent to C. Since a RAC score of 1 represents highest risk, it follows that risk for a site s, as measured by RAC_s, the RAC score of s, is proportional to 5- RAC_s. Thus, for case (a), the *risk associated with site s* is defined by

$$RISK_s = W_{copop} * Pco_s * [1 + W_{RAC} * (5 – RAC_s)],$$

where Pco_s is the population of the county containing site s, and W_{copop} and W_{RAC} are weighting factors that are independent of s. The assignment of values to weighting factors is discussed in Chapter 4.

Specifically, if RAC_s=5, then, as indicated in the Section 2.1, there is still some risk associated with s, namely

$$RISK_s = W_{copop} * Pco_s$$

and this risk is increased by

$$(\text{RISK INCREMENT})_s = W_{copop} \ * \ Pco_s \ * \ W_{RAC}$$

each time RAC_s is decreased by 1. For case (b), the risk associated with site s is defined by

$$RISK_s = W_{copop} \ * [\ Pco_s + W_{nbrcopop} * Pnbrco_s] * [\ 1 + W_{RAC} * (\ 5 - RAC_s) \ ],$$

where $Pnbrco_s$ is the sum of populations of all counties neighboring C, and $W_{nbrcopop}$ is a weighting factor that is independent of s.

SICLUPS uses case (a) for sites in California and case (b) for sites in Florida; reasons for this are given in the Appendix F.

The *risk reduction due to remediation* of a site s is defined as the risk associated with s.

The weighting factors are parameters that are input to the optimization programs.

2.3 How is value measured?

For any schedule of site remediations, the SICLUPS model assigns a VALUE to each remediation. The value of a site remediation that is completed in time segment t is defined to be the sum of two parts:

VALUE(t) = VALUE DUE TO RISK REDUCTION(t) + VALUE DUE TO LAND REUSE(t).

Generally, the earlier the time segment in which remediation of a site is completed, the greater the value of this remediation. Since it follows from assumption #5 in Section 1.3 that no remediations are completed in the first time segment, we first consider the second time segment, t=2, where the two quantities on the right-hand side of the above formula are as follows:

VALUE DUE TO RISK REDUCTION(2) = RISK REDUCTION DUE TO REMEDIATION,

where the latter was defined in Section 2.2, and

VALUE DUE TO LAND REUSE(2) = W_{ac} * NUMBER OF ACRES ON SITE,

where W_{ac} is a weighting factor. For each time segment that the schedule delays remediation of a site beyond the 2^{nd} time segment , these values are reduced by being multiplied by a discounting factor VALDISCT in the range:

$$0 < \text{VALDISCT} < 1.$$

VALDISCT, W_{ac}, and the other weighting factors, introduced in Section 2.2, are parameters that are input to the optimization program.

2.4 What is optimum?

The schedule of site remediations which the MIP procedure attempts to find is that schedule, among all possible schedules, which maximizes the total value:

$$\sum_{s} \mathrm{VALUE}_s\,(t_s),$$

where the summation is over all sites remediated, and t_s is the time segment in which site s is remediated.

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3 MODEL OVERVIEW

3.1 Introduction

The basic SICLUPS optimization model is a mixed-integer linear program (MIP) that finds the optimal way to schedule and allocate funds for site remediations at the time segment level, for the definition of optimality given in Chapter 2, for the set of 126 sites introduced in Chapter 1 and described in the next section. The model was run with different combinations of values for budgets and other parameters, such as the weighting factors W_{copop} and W_{RAC} that were defined in Chapter 2. Using the GAMS/OSL solver on an IBM RISC/6000 machine, computing times varied from approximately 3 minutes to 12 hours.

Variations on the basic SICLUPS model were also developed. A variation with a somewhat smaller set of sites and a variation with some added constraints were developed and tested. It was found that certain alterations of the model resulted in substantial savings in computing time. Results for these variations on the basic model are presented in the Appendix G.

3.2 Data inputs

The set of sites for the basic SICLUPS model was introduced in Chapter 1. The model requires a list of sites, and, for each site, the county containing the site, cost estimates for the 3 phases of remediation described in Chapter 1, the number of acres on the site, and a RAC score. The Risk Assessment Code (RAC) score was introduced in Chapter 2.

The U. S. Army Corps of Engineers (USACE) maintains a list of properties eligible for remediation under the DERP-FUDS program and labels them with property numbers. Each of these properties has been sub-divided by AEC into sub-sites. The cost estimates and acreages supplied by the AEC are for the sub-sites, where available. There were many instances in which cost estimates were available for only some of the sub-sites of a USACE-designated property, so in the SICLUPS models, a site that is referenced by a USACE-assigned property number may actually be only a portion of this property.

Apart from these gaps in the data, we had some choice as to the specification of sites for the SICLUPS models. We could define a site to consist of either (1) all sub-sites of a USACE-designated property for which cost estimates are available or (2) only some of these sub-sites. A site was chosen to be as large a portion of a USACE-designated property as possible, consistent with the rule that the total remediation cost for a site may not exceed $40 million.

Sites were selected from each of the 3 geographic regions listed in Chapter 1. For each region, all sub-sites of FUDS properties for which AEC supplied complete cost estimates were considered, and sites for the models were chosen on the basis of the “$40 million” rule in the preceding paragraph. The results for the 3 geographic areas were as follows:

For Florida, sites were made from 24 USACE-designated FUDS properties; of these, the following two properties were split into two sites each: I04FL0287 and I04FL0405. The result was a model with 26 sites.

For the Los Angeles district, sites were made from 77 USACE-designated FUDS properties; of these, property J09CA0278 was split into three sites, and property J09CA0284 was split into two sites. The result was a model with 80 sites.

For the San Francisco and Sacramento districts, a site was made from each of 20 USACE-designated FUDS properties.

These three models were combined into the full-sized SICLUPS model of 126 sites.

The file of cost estimates obtained from AEC had, in addition to “expected” cost estimates, “best case” and “worst case” cost estimates. Only the “expected” cost estimates were used.

The RAC score assigned to a site in a SICLUPS model is that assigned to the corresponding USACE-designated property, if there is such a score. Otherwise, the site is given a RAC score of 5.

The assignment of the value $RAC_s = 5$ for sites s for which no RAC score is available is a guess, based on the following reasoning: Managers at USACE collect risk data for all FUDS, as it becomes available, and in considering for which of the large number of sites to compute RAC scores, they give priority to sites which appear to have substantial risk. We inferred that if a site was not assigned a RAC score by USACE, then it is a sign that the managers there consider it to be associated with less risk than most of the sites to which they have assigned RAC scores.

3.3 Model formulation

The SICLUPS optimization model is a mixed-integer programming model. The model formulation is as follows:

Indices:

s – sites

p – phases of remediation

t – 6-year time segments

Binary variables (must have value either 0 or 1):

$I_{s,p,t}$ = 1 if and only if funding is allocated for phase p of remediation of site s during time segment t.

$E_{s,p,t}$ = 1 if and only if phase p of remediation of site s is completed at the end of time segment t or sooner.

Continuous-valued decision variables:

$a_{s,p,t}$ = funding allocated for phase p of remediation of site s during time segment t

Data:

b_t = budget for time segment t
$c_{s,p}$ = cost of phase p of remediation for site s
Pco_s = population of the county C(s) containing site s
$Pnbrco_s$ = sum of populations of counties bordering on county C(s)
RAC_s = Risk Assessment Code (RAC) score for site s
a_s = acreage in site s

Objective function:

Maximize Total Value of site remediations = $\sum_s$ VALUE OF REMEDIATION OF SITE s,

where the summation is over the set of all sites remediated.

The objective function maximizes the total value of site remediations, as defined in Chapter 2. Here, value is to be understood not as a monetary value but as an abstract quantity which represents the extent to which some combination of Army UXO program goals, including safety, health, environmental protection, and land reuse, is achieved via the remediations.

A technical point for solution of the MIP problem is that, in order to apply a mathematical algorithm to solve the problem, the objective function must be formulated as the sum of a fixed number of terms. The number of terms in the sum in the above formula for the objective function is the number of sites remediated. The objective function is actually formulated in terms of the binary decision variables $E_{s,p,t}$.

Constraints:

$$\sum_{s} \sum_{p} a_{s,p,t} \leq b_t, \forall t \qquad (1)$$

Constraint 1 insures that total expenditures are within budget for each time segment.

$$\sum_{t} a_{s,p,t} \leq c_{s,p}, \forall s,p \qquad (2)$$

Constraint 2 insures that the total amount allocated for a task does not exceed its cost.

$$E_{s,p,t} = \sum_{t'<t} a_{s,p,t'} / c_{s,p}, \forall s,p \qquad (3)$$

Constraint 3 insures that a task is not considered complete until the total funds allocated for it equal the cost of the task.

$$\text{minfund} * I_{s,p,t} \leq a_{s,p,t}, \forall s,p,t \qquad (4)$$

Constraint 4 insures that if funds are allocated for a task during a time segment, then funding must be at a level at least “minfund”, where “minfund” is a model parameter.

$$a_{s,p,t} / c_{s,p} \leq I_{s,p,t}, \forall s,p,t \qquad (5)$$

Constraint 5 insures that $I_{s,p,t}$ is positive only if funds are allocated for phase p of remediation of site s during time segment t.

$$I_{s,3,t} \leq E_{s,2,t}, \forall s,t \qquad (6)$$

Constraint 6 insures that, at a given site, phase 3 of the remediation cannot begin until the same time segment that phase 2 is completed or a later time segment.

$$I_{s,2,t} \leq E_{s,1,t}, \forall s,t \qquad (7)$$

Constraint 7 insures that, at a given site, phase 2 of the remediation cannot begin until the same time segment that phase 1 is completed or a later time segment.

$$I_{s,p,t} \leq 1 - E_{s,p,t-1} \text{, when } t > 1, \forall s,p,t \qquad (8)$$

Constraint 8 insures that if a task is complete by the end of one time segment, then no further work is to be done on this job in any later time segment.

$$I_{s,p,t} \geq I_{s,p,t-1} - E_{s,p,t-1}\text{, when } t > 1, \forall s,p,t \qquad (9)$$

Constraint 9 insures that if a task is not complete by the end of a time segment, prior to the last time segment, then work on this job is to be continued in the next time segment.

$$\sum_{p} I_{s,p,t} \leq 2, \forall s,t \qquad (10)$$

Constraint 10 insures that at most two phases of remediation at a given site will be carried out during any one time segment.

The SICLUPS optimization program solves for choice of the amounts of funding for all of the tasks in the model, i.e., for all of the site-phase combinations, for all of the time segments, that maximizes the total value of site remediations, while meeting the 10 constraints. This solution is what we refer to as the *optimal* schedule of site remediations. Thus, the optimal schedule of site remediations depends on model data and on model parameters, including the weighting factors in the definition of value.

4 APPLICATION TO ARMY UXO PROGAM GOALS

4.1 Choosing values for weighting factors according to desired goals

A number of Army UXO program goals that can be addressed by SICLUPS were described in Chapter 1. Army managers who use the SICLUPS methodology who have a preference for one or more of these specific goals are free to assign values to the weighting factors and other parameters in the SICLUPS model in a way such that the resulting VALUE function, defined in Chapter 2, represents these goals. For example:

1. If the manager's goal is to maximize the number of acres remediated or the number of acres remediated per million dollars spent, then the manager chooses W_{ac} large compared to the other three weighting factors, W_{RAC}, W_{copop}, and $W_{nbrcopop}$.

2. If the manager's goal is to maximize the number of people to whom risk of injury is reduced, then the manager chooses W_{copop}, and possibly also $W_{nbrcopop}$, large compared to W_{ac} and W_{RAC}.

3. If the manager's goal is to maximize the extent to which severity of injury to people is reduced, then the manager chooses W_{RAC} larger than the other three weighting factors.

4. If the manager wishes to substantially reduce *both* the number of people at serious risk *and* the expected severity of possibly injury, as estimated by the RAC score, then the manager chooses *both* W_{copop} and W_{RAC} large compared to W_{ac}.

5. If the manager wishes to decrease the length of time taken to remediate the higher-risk sites, then the manager decreases VALDISCT, so as to increase the penalty for delaying the remediation of higher-risk sites.

4.2 Using post-processing to examine how well program goals are achieved

The output of the SICLUPS optimization program can be input to the post-processing program, which gathers statistics on the solutions pertinent to Army UXO program goals, listed in Chapter 1. Army managers who use the SICLUPS model can carry out multiple runs of the model with different combinations of values for model parameters for different runs. For each run of the model, they can examine the statistics output by the post-processing program, and on the basis of a comparison of results for different runs, they can decide which solution of the scheduling problem they like best among all solutions examined. This comparison process will be illustrated with a case study in the following section.

A detailed description of the output of the post-processing program is provided in the Appendix I.

4.3 A case study using post-processing

Three specific cases of the basic SICLUPS model were chosen. The only parameter whose value is changed in going from one of these models to another is the parameter W_{RAC}, which has values 0, 1, and 2, as indicated in the legends of the graphs.

These three specific cases are but three of many possible specific cases, determined by many possible combinations of values of the parameters in the VALUE function, defined in Chapter 2. The kind of comparative analysis of optimization results for different specific cases that can be performed by the post-processing code, including trade-off analyses for two or more potentially conflicting Army UXO goals, is illustrated in this section for these three specific cases.

Post-processing results are presented graphically in Figures 2-7. In the figures, the weighting factor W_{RAC} is called RACWT.

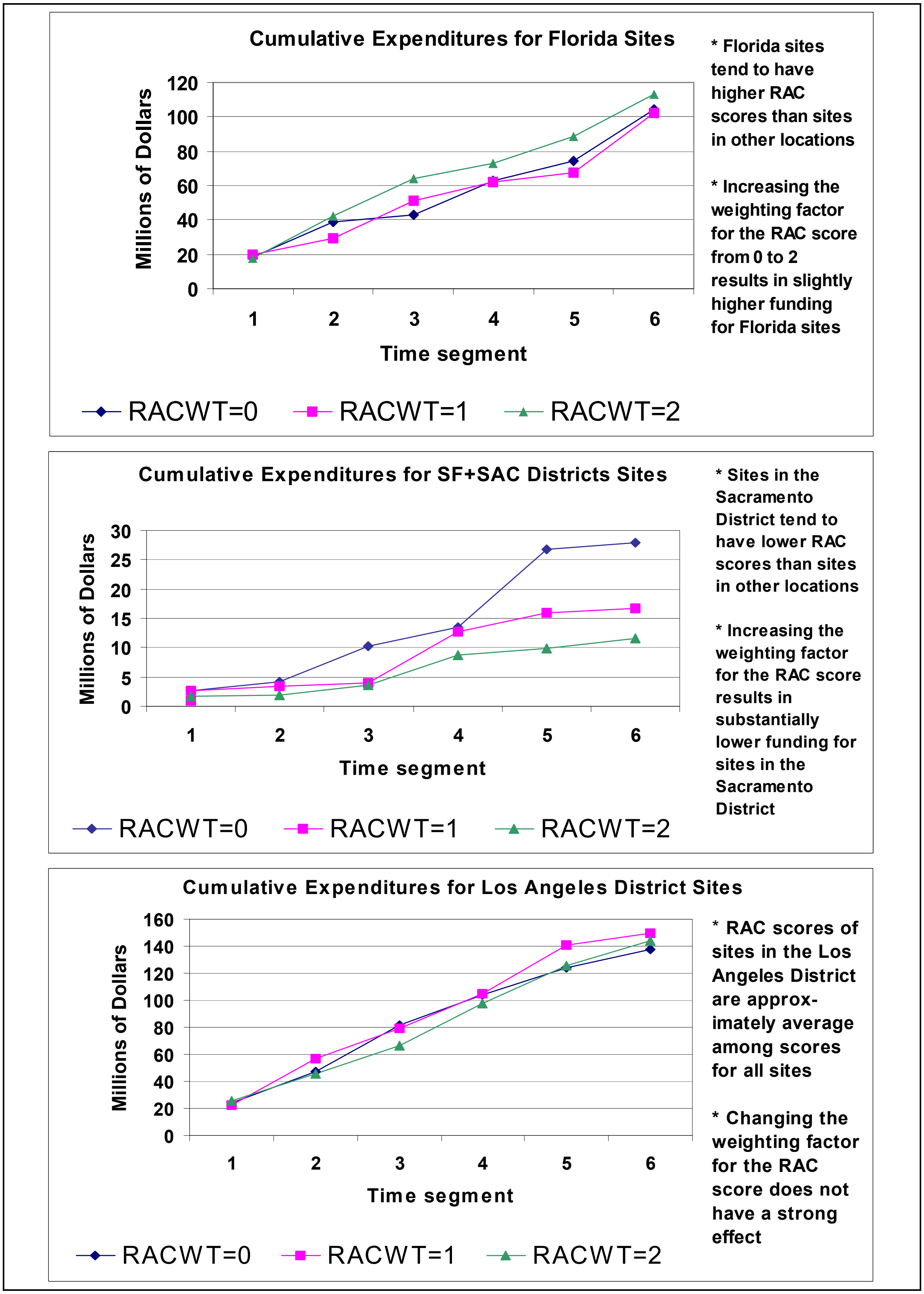

Figure 2. Cumulative expenditures for the 3 main geographic areas

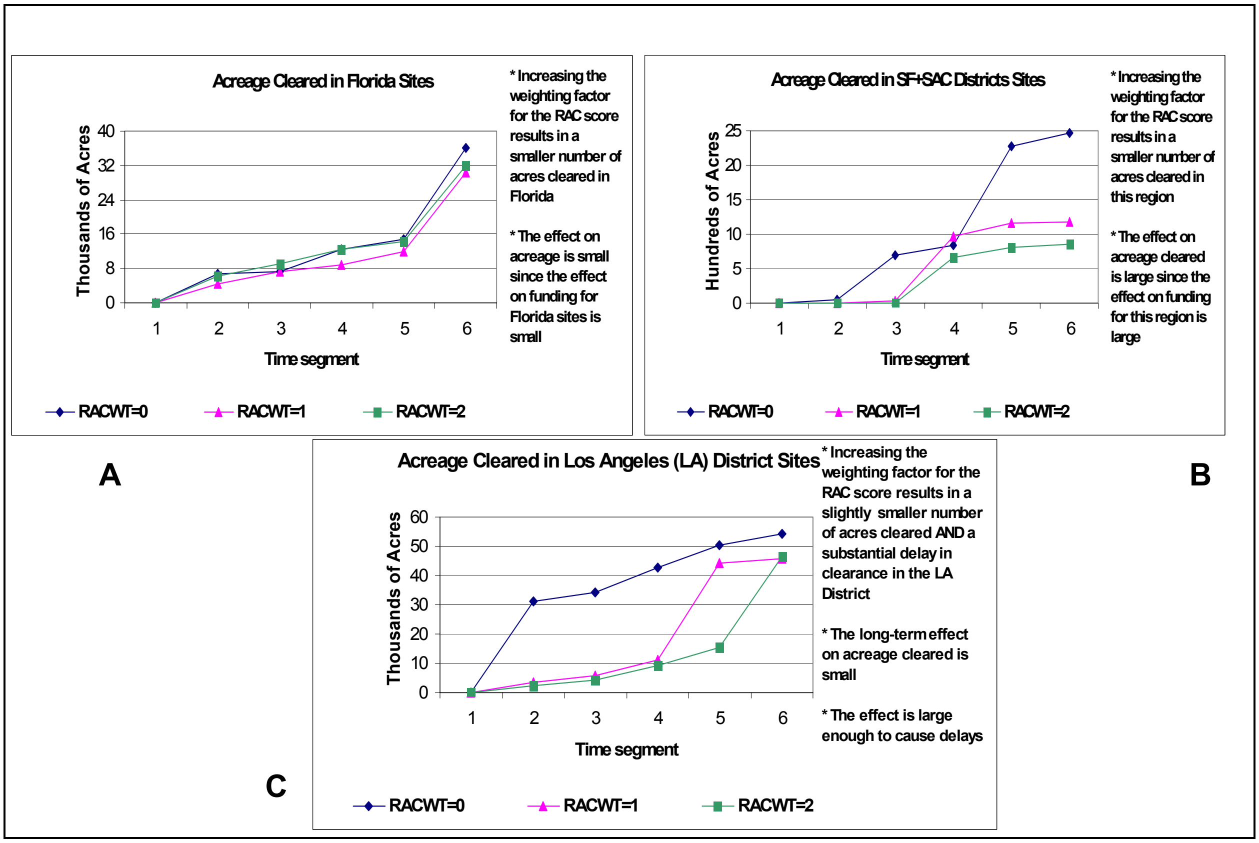

Figure 3. Acreage cleared for the 3 main geographic areas

Figure 2 shows results from the 1st block of statistics output by the post-processing program – cumulative expenditures for the 3 geographic areas in the model. Since the sites in the 3 areas are competing with each other for the same funding, one area can gain only at the expense of another area losing, as one goes from one W_{RAC} value to another. One can see that increasing W_{RAC} has the effect of favoring areas with sites with higher RAC scores: as W_{RAC} increases to 2, more remediation is done in Florida, whose sites tend to have higher RAC scores, and less remediation is done in the San Francisco and Sacramento Districts, whose sites tend to have lower RAC scores. The effect on the Los Angeles District, whose sites tend to have intermediate RAC scores, is minimal.

Figure 3 shows results from the 2nd block of statistics output by the post-processor – cumulative acreage cleared. The general pattern of results here is roughly the same as for Figure 2 – overall, acreage cleared is approximately proportional to funding. From Fig. 3C, one sees that the effect of increased W_{RAC} in the Los Angeles District is more to delay than to omit remediation of sites. In Fig. 3B, one sees that increasing W_{RAC} from 0 to 2 results in approximately 1700 fewer acres are remediated in the San Francisco and Sacramento Districts.

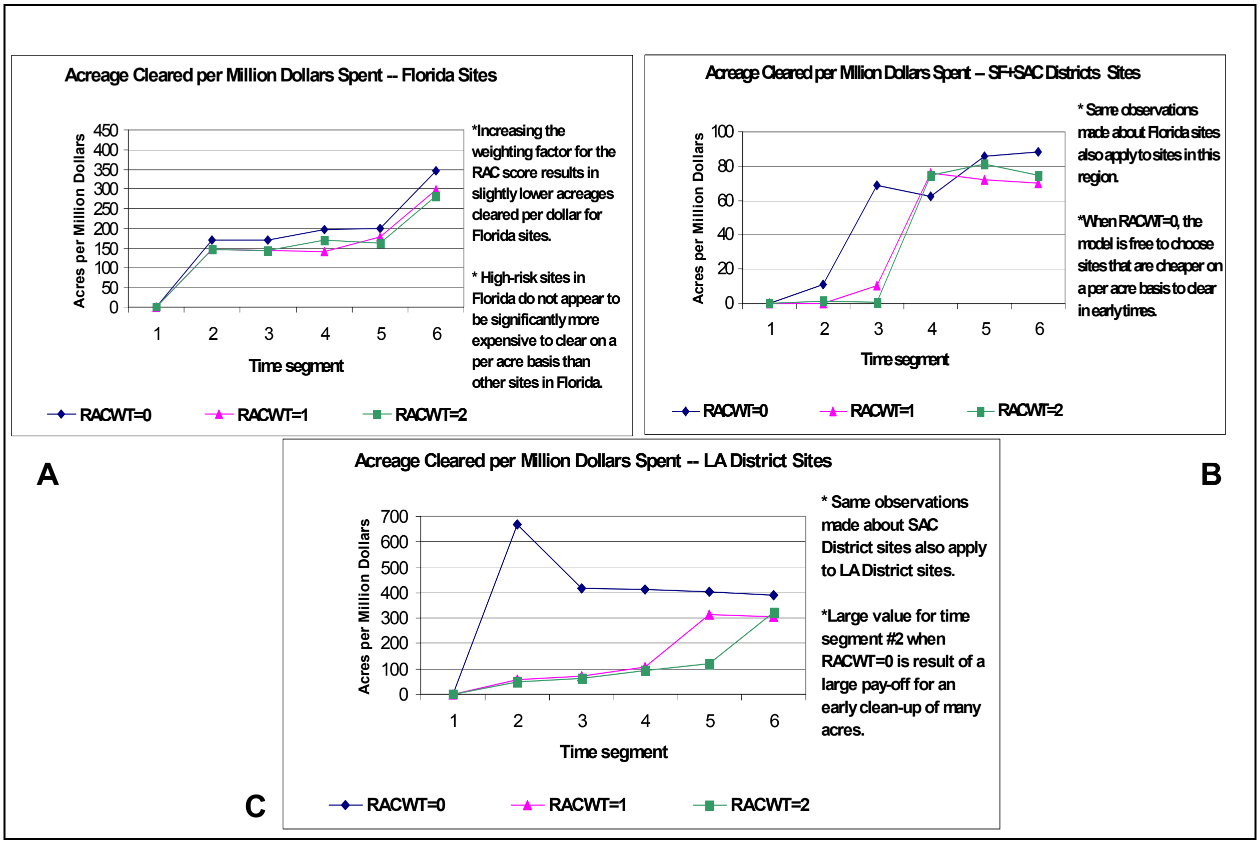

Figure 4. Acreage cleared per million dollars spent for the 3 main geographic areas

Figure 4 shows results from the 3rd block of statistics of post-processing output – acreage remediated per million dollars spent. Values of this quantity tend to be smaller for positive W_{RAC} than for W_{RAC} =0, so that giving higher priority to remediating sites with high RAC scores is achieved at the expense of having fewer acres cleared per million dollars spent.

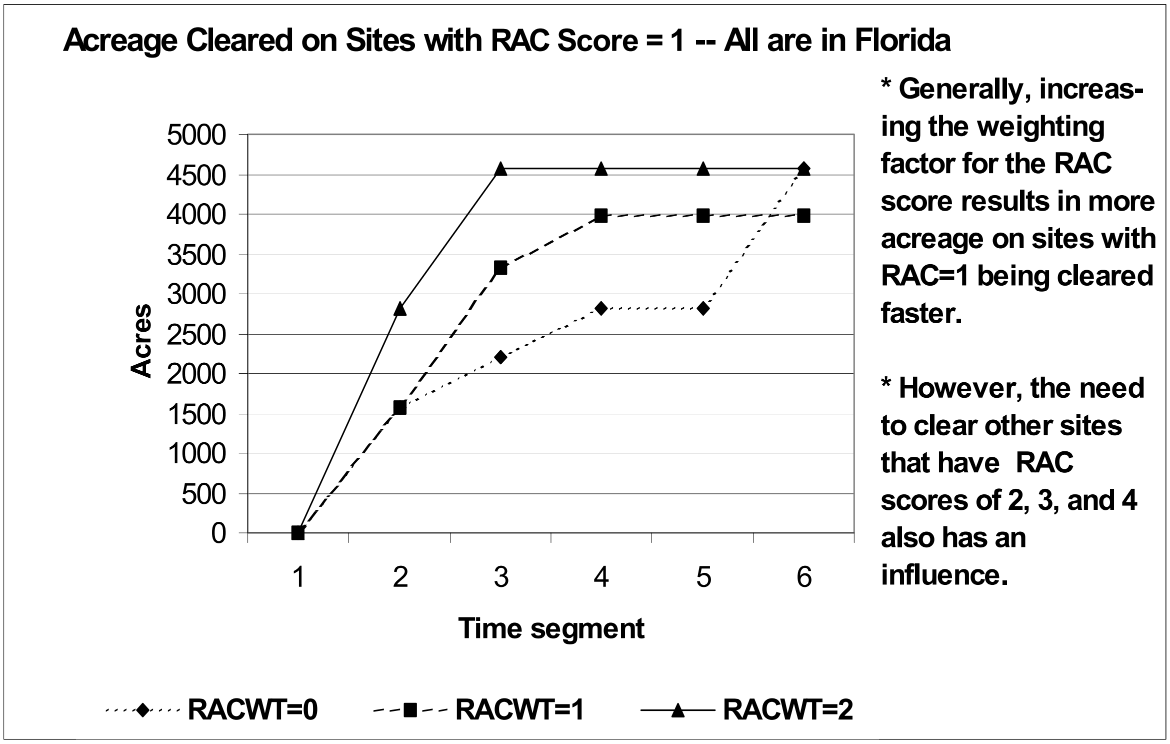

Figure 5. Acreage cleared on sites with RAC = 1

Figures 5 and 6 show results from the 4th and 5th blocks of statistics of post-processor output – acreage remediated on sites with RAC score equal to 1 and 2, respectively. It happens that all of sites with RAC=1 are in Florida. One sees the same variation of results with W_{RAC} that was noted above for other quantities. Overall, it seems that sites with RAC=1 tend to be remediated during the first 3 time segments, and those with RAC=2 during the first 4 time segments. For acreage cleared on sites with RAC=2, the qualitative similarity of graphs in Figures 6A and 6C seems to reflect the dominance of the Los Angeles District in determining this statistic.

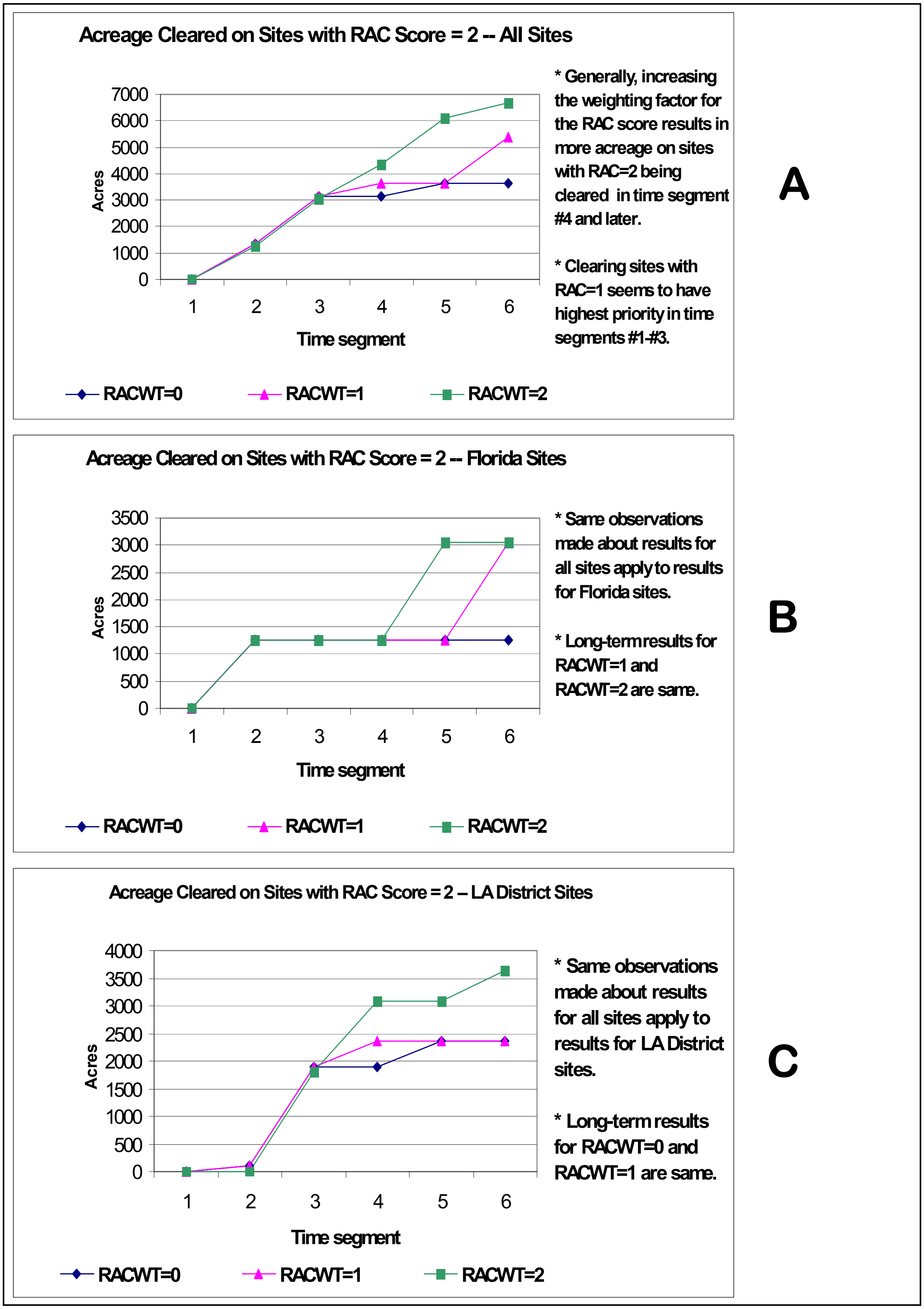

Figure 6. Acreage cleared on sites with RAC=2

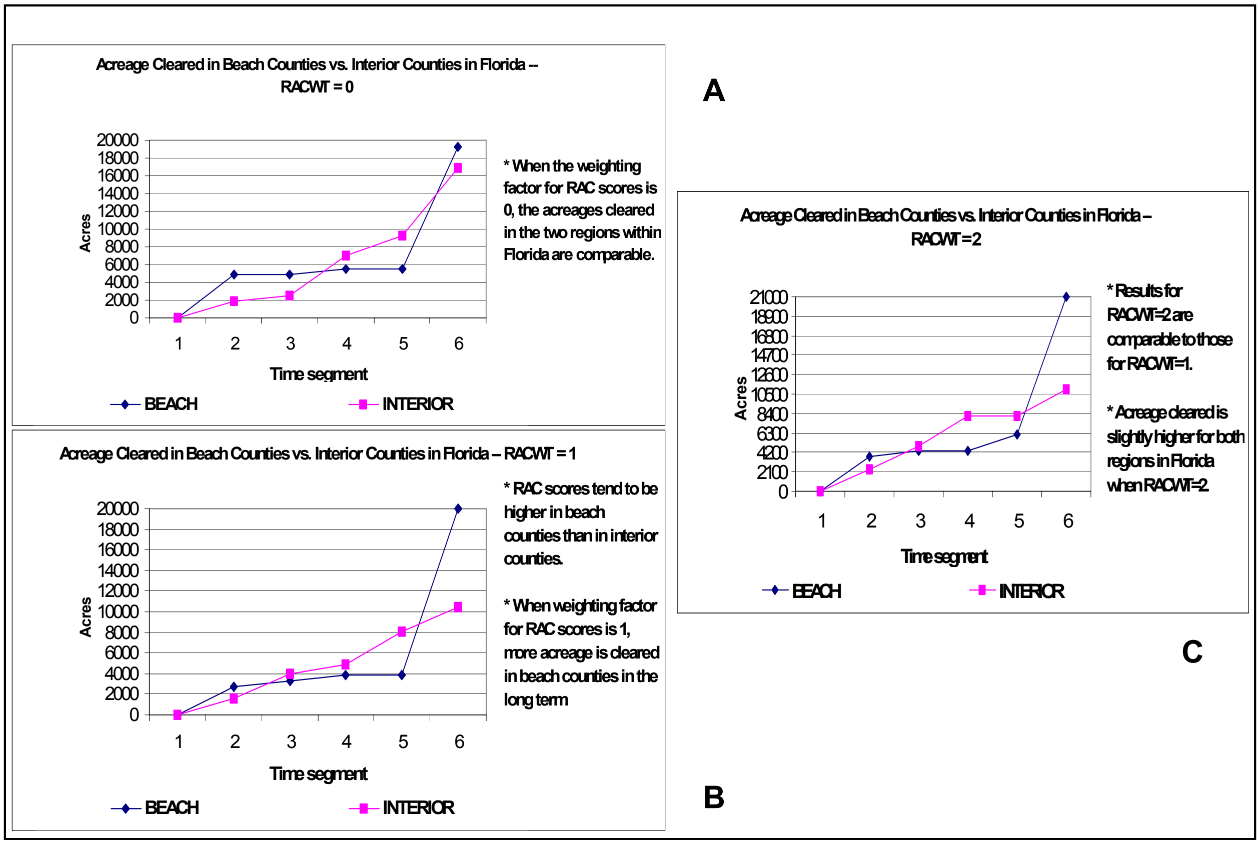

Figure 7. Acreage cleared in beach counties vs. interior counties in Florida

Figure 7 shows results from the 6th block of statistics of post-processor output – breakdown of acreages for 3 sub-areas in Florida. The presentation of statistics in Figure 7 is different from that of previous triples of figures labeled A-C – in Figure 7, there is a separate graph for each of the 3 values of W_{RAC}, and within each graph results for beach counties are easily compared with those for interior counties. One can see the effects of increasing W_{RAC} both in Florida as a whole and within the 2 sub-areas – they are qualitatively the same as was noted above in reference to earlier figures. The Orlando area and the beach areas are of particular interest from the standpoint of risk, because of the large number of people who visit these areas from out of state. The graph of acreages cleared in the Orlando area for the 3 values of W_{RAC} is qualitatively very similar to that in Figure 5, and so is not shown here.

The 7th block of statistics of post-processor output gives a breakdown of acreages for 3 sub-areas in the San Francisco and Sacramento Districts. Examining Fig. 3C above, we saw that increasing W_{RAC} from 0 to 2 resulted in approximately 1700 fewer acres remediated in the San Francisco and Sacramento Districts. The 7th block of statistics shows that approximately 50 of those 1700 acres are in the densely populated Bay Area.

The 8th block of statistics of post-processor output gives a breakdown of acreages for the 3 sub-areas in the Los Angeles District indicated in Figure 1. For both sub-areas, one has the same variation with W_{RAC} that has already been noted for other areas. W_{RAC} can make a big difference in these two sub-areas, because there are sites in counties with relatively low populations having high RAC scores. For example, the site in El Centro, in sparsely populated Imperial County, whose USACE property number is J09CA0147, will be remediated if W_{RAC} =2 but not if W_{RAC} =0 or 1.

Detailed consideration of how choice of goals affects acreage cleared on sites in the highest risk category (RAC=1).

If the Army manager's goal is to maximize the extent to which severity of possible injury to people is reduced, then it is appropriate for the manager to choose a relatively large number for W_{RAC} , such as W_{RAC} =2.

If the manager's goal is to maximize the number of people to whom risk of injury is reduced, without consideration of the severity of such injury, then the manager would want the objective function to measure density of people in the vicinity of each site, and so would choose W_{RAC} =0.

The consequences of these two possible parameter choices for acreage cleared on sites with RAC=1 are shown in Figure 5.

If W_{RAC} =2, then all of the sites in the highest risk category are remediated by the end of time segment #3 (18 years).

By contrast, if W_{RAC} = 0, then

1. not until the end of time segment #6 (36 years) will all sites in the highest risk category be remediated
2. more than 35% of the acreage on sites in the highest risk category will still not be remediated by the end of time segment #5 (30 years), and, as a result,
3. risk of injury in Florida will be greater than for the case of W_{RAC} =2, due to an additional 2-3 time segments (12-18 years) of delay in clearing the remaining 35% of the land in the highest risk category.

Choosing W_{RAC} =1 will cause RAC scores to have a small effect on the objective function, too small an effect to produce consistent results.

Remediation costs are approximately the same for all three cases.

4.4 Comparing model results directly from optimization program outputs

If, for the above case study, the managers who use SICLUPS want to choose, for example, between the parameter value W_{RAC} =0 and the parameter value W_{RAC} =2, then, as shown in the Section 4.3, they can compare the summary statistics for these two models output by the post-processor, as described there. Alternatively, they can perform a more detailed comparison of the results of the two models than is output by the post-processor, by directly comparing the outputs of the optimization program. They may wish to consider, for example, which specific sites are remediated for one case but are not remediated for the other. For W_{RAC} =0, the site in Marion County, Florida having USACE property number I04FL1130 will be remediated, but the site in California with USACE property number J09CA0147, referred to in Section 4.3, will not be remediated. For W_{RAC} =2, the situation is reversed: site J09CA0147 will be remediated, but site I04FL1130 will not be. The managers may wish to consider other data not represented in the SICLUPS models: What are the population trends for the two counties containing these two sites? For each, is the county's population expected to increase substantially in the coming 5 to 10 years? What about neighboring counties? Is development expected in the immediate vicinity of the sites? Is an interim measure, such as fencing off part or all of the site, practical? If fencing is installed, what costs should be expected for its maintenance? Will this cost be affected by precipitation or/and soil erosion in the next 5 to 10 years?

From the outputs for the two runs of the SICLUPS optimization codes for the two cases W_{RAC} =0 and W_{RAC} =2, the user can find

(1) all of the sites remediated for W_{RAC} =0 but not for W_{RAC} =2, and

(2) all of the sites remediated for W_{RAC} =2 but not for W_{RAC} =0

and may consider specific questions, similar to those raised above for sites I04FL1130 and J09CA0147, for all of these sites. In particular, for either of the two models and for any site s in the model, the manager can find whether remediation of s was completed and, if so, during which of the 6 time segments it was completed.

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5 DETERMINATION OF SCHEDULES AT THE YEAR-BY-YEAR LEVEL

5.1 Two levels of resolution of the time scale in SICLUPS

The SICLUPS methodology involves working with two levels of resolution of the time scale. Since the Army works with annual budgets, decisions for site remediation must be made in terms of amounts to be allocated for tasks from each annual budget. But because the overall UXO remediation problem is costly in comparison to the amounts allocated for UXO in annual budgets, UXO remediation of all of the eligible FUDS in the CONUS is expected to take decades. Because of this and because of computational complexity considerations for the SICLUPS optimization programs, we decided to use 6-year time intervals for the time segments in the mixed-integer programming (MIP) formulation of the scheduling problem.

The result is that the SICLUPS methodology involves working with two different levels of resolution of the time scale. One begins with a 36-year time line, with a budget for each of the 36 years and a list of sites that need to be remediated. One then partitions the 36-year time-line into 6 time segments and combines the budgets of the six years of each time segment into a budget for the whole time segment. The MIP problem is formulated and solved for this scheduling problem – the solution tells one what amounts to allocate to the various remediation tasks from the budgets of the 6-year time segments. For this solution to be useful to the Army, it must be converted into a form that conforms to Army procedures, namely it must tell one what amounts to allocate for tasks from *annual* budgets – it must be refined to the year-by-year level.

5.2 A simple method for refining schedules to the year-by-year level

There is a simple method of refining the schedule at the time segment level to a schedule at the year-by-year level that works fairly generally – it works for all cases where annual budgets of all years within a time segment are equal. It will be illustrated in this section for one of the specific cases which was analyzed in Chapter 4, specifically for the case analyzed in Section 4.3, for which $W_{RAC} = 0$.

The procedure is as follows: For each time segment, consider the set of sites for which remediation is to be done during this time segment – for time segment t let this set of sites be called S_t. For each t and each site in S_t, let the combined task for this site be the combination of all tasks for this site for time segment t. Thus, there are 5 possibilities for the combined task: phase 1, phase 2 , phase 3, phases 1 and 2, or phases 2 and 3. Now, let the cost of the combined task for each site in S_t be defined in the obvious way – as the sum of the costs of the individual tasks comprising it. Then, for each year in time segment t, let an amount equal to 1/6 of the cost of each combined task be allocated from the annual budget to this combined task.

This procedure, with the sets S_t of sites and the sets of combined tasks associated with these sites, for the case of the run of the SICLUPS model analyzed in Section 4.3 with $W_{RAC} = 0$, can be understood with the aid of the information about the results of this run, shown in Figures 8 and 9. For the first time segment, we have the set S_1 of sites, whose members are the 46 sites listed in Figure 8. The set of combined tasks for S_1 consists of:

* phases 1 and 2 combined, for each site in columns 1 and 2 of Figure 8 and for sites F0287a, C0710, and C7044.
* phase 1 alone, for each site in column 3 of Table 1 other than F0287a, C0710, and C7044.

One can similarly read off S_t and its associated list of combined tasks for each t, $2 \le t \le 6$. The set of combined tasks for S_t sometimes contains combinations of phases 1 and 2 and sometimes contains combinations of phases 2 and 3.

For allocation of funds, consider, for example, site F0179. As shown in Figure 9 on page 29, the combination of phases 2 and 3 for this site is to be funded in time segment #6. How funding of this task will be covered by the individual years of the time segment is determined as follows: the total cost T for the combined task is $c_{F0179,2} + c_{F0179,3.}$ The amount from each of the 6 years of the time segment to be allocated for the combined task is T/6. From the cost data we have $c_{F0179,2} = 0.0177*T$ and $c_{F0179,3} = 0.9823*T$, so from the budget of the 1st year of the time segment, funds are allocated for the full cost of phase 2 and funds in the amount of (0.1667-0.0177)*T = 0.149*T are allocated for phase 3. For each of the remaining years of the time segment, funds in the amount of T/6 are allocated for phase 3.

The names of specific sites in the section are abbreviations of the names of the USACE-designated FUDS properties containing them, with a final letter "a", "b", or "c" appended in some cases. The initial "F" or "C" is the initial of the state containing the site.

For the case of Section 5.2
Of the 83 sites completely remediated, sites for which phase 1 is scheduled for time segment #1, according to the schedule at the time segment level

1	2	3
F0197	F0124	F0287a
F0203	F0227	F0405a
F0230	F0377	F0405b
F0401	F0698	F0891
F0856	F0890	F0914
C0877	F0894	C0691
C3107	F0895	C0710
C0150	F0912	C1130
C0198	F1065	C7044
C0209	F1129	C7313
C0214	F1167	C7315
C0215	C0186	
C1069	C0273	
C1110	C0587	
C1120	C0685	
C7115	C0696	
C7236	C7153	
	C7347	

Figure 8. Sites for which phase 1 is scheduled for time segment #1 for case of Section 5.2

For the case of Section 5.2
Of the 83 sites completely remediated, sites for which the 3 phases are to be carried out in the various time segments, according to the schedule at the time segment level

time segment:

	#1	#2	#3		#4		#5		#6
PHASE 1	Sites in Figure 8	F0426 C0876 C0675	C0950 C1039 C7287 C0145 C0170 C0184 C0672 C0679 C0680	C0688 C0689 C7074 C7129 C7329	F0287b C0781 C1074 C7293 C7466	C0156 C0674 C0676 C0677 C0690 C0695	F0179 F1130 C0094	C0181 C0182 C0185 C0681 C0686 C0692	
PHASE 2	All sites in columns 1 & 2 of Figure 8 and F0287a C0710 C7044	C0675	F0426 F0891 C0876 C7287 C0145 C0184	C0679 C0689 C1130 C7329	F0287b F0405b F0914 C1039 C1074 C7466	C0672 C0680 C0695 C7074 C7129	F0405a F1130 C0094 C0781 C0950 C7293 C0156 C0170 C0182	C0674 C0676 C0677 C0681 C0688 C0690 C0691 C7313 C7315	F0179 C0181 C0185 C0686 C0692
PHASE 3		All sites in columns 1 & 2 of Figure 8 except for C0209, C7236, & F1065 and C0710 C7044	F0891 C0876 C0209 C0675 C1130		F0287a F0405b F0426 F0914 C1039 C0145 C0184 C0672 C0679 C0680 C0689	C7074 C7129 C7329	F0287b F1065 C0781 C0950 C1074 C7287 C7293 C7466 C0156 C0170 C0674	C676 C677 C688 C690 C691 C695 C7236 C7315	F0179 F0405a F1130 C0094 C0181 C0182 C0185 C0681 C0686 C0692 C7313

Figure 9. Schedule at the time segment level for case of Section 5.2

The reasoning behind the way that sites were assigned to the 3 columns in Figure 8 is clarified in the description of another method of refining the schedule to the year-by-year level, given in Appendix K.

5.3 Other methods of refining schedules to the year-by-year level

The specific method of refining the schedule at the time segment level output by the SICLUPS optimization program, given in the preceding section, is a simple method that works quite generally. One of the consequences of this method is that the allocation of funds for a task is often split over several years. There may be practical difficulties with this fragmentation of the funding. For example, carrying out the task might require a contract whose cost exceeds the amount allocated for the task in one year. If the Army managers who determine the schedule find this fragmentation undesirable, they can attempt to find other ways to refine the schedule to the year-by-year level. In Appendix K, a different method of refining to the year-by-year level is applied to the same run of the model as that discussed in Section 5.2. The application of the method to this case gives a schedule in which (1) funding for phase 1 is less fragmented, being

spread out over only 2 years for all sites, and (2) funding for phase 2 is covered in 1 year for most sites. The issue of how generally the method applies is discussed in Appendix K.

6 SUMMARY

6.1 Modifications of the basic SICLUPS model

The basic SICLUPS model was introduced in Chapters 1-3. Modifications of the basic model have been developed. The first modification involved reducing the number of sites from 126 to 108. The second modification involved adding some more constraints to the MIP problem formulation. Computing times for runs of these models, with various combinations of values for certain parameters, have been studied. It was found that for many cases, there was a substantial savings in computing time to be gained from using the modified model. A savings in computing time may be of great practical value to Army managers applying the SICLUPS methodology, since they may wish to have many runs made of a model with different values for weighting factors and other parameters in the definition of VALUE, as described in Chapter 4.

The modified models and computing times for test runs are described in Appendix G.

6.2 Findings

(1) We have solved the problem of determining the optimal scheduling and allocation of funds for UXO remediation of over 100 formerly used defense sites over a 36-year time period, for the basic SICLUPS model and for two modifications of the basic model. For these models, the basic time units are 6-year time intervals. Solutions have been obtained for many combinations of specific values of model parameters.

The basic SICLUPS model was described in Chapters 1-3, and the modifications are described in Appendix G.

(2) We have shown that different choices of parameter values, representing different weighted combinations of Army UXO program goals, lead to different remediation schedules. We have demonstrated meaningful trade-off analyses comparing schedules that correspond to different goals.

(3) The computer programs that compute the optimal schedules can easily be adapted to any set of sites for which the necessary data is available – no extensive rewriting of GAMS code would be needed.

(4). There are straightforward ways to refine the schedules whose basic time units are 6-year intervals to schedules whose basic time units are years.

(5) We found many cases where computing times for our implementation of the 126-site MIP model was under one hour.

(6) Model validity is affected by detailed specification of remediation procedures, costs, and lengths of time needed for the various phases of remediation.

Cost estimates for each of 3 phases of remediation are model inputs. The model's basic assumption about the lengths of time needed is embodied in constraint #10 in Section 3.3.

(7) The SICLUPS procedure can be an objective way to determine the scheduling and funding for site remediations; that is, to make the determination in a way that minimizes the effects of personal biases, such as a bias in favor of a specific state or Congressional district.

6.3 Recommendations

The recommendations are as follows:

(1) That Army managers use the SICLUPS methodology to determine tentative optimal site remediation schedules for the FUDS program and possibly for other clean-up programs.

(2) That Army managers use the SICLUPS methodology to reconcile conflicting priorities represented by different Army UXO programming goals, by performing trade-off analyses that compare different schedules.

(3) That Army managers use the SICLUPS methodology to objectively determine how to divide funding for UXO clean-ups of former DoD ranges among the various Corps of Engineers divisions and districts.

(4) That further efforts be made to improve cost estimates of site clean-ups.

(5) That site remediation schedules be updated on a regular basis, and that the best cost estimates available be used each time a schedule is updated.

APPENDIX A PROJECT CONTRIBUTORS

1. PROJECT TEAM

a. Project Director. David S. Anker

b. Other Contributors. Marie J. Vanderpool, LTC William J. Tarantino, Linda A. Coblentz

2. PRODUCT REVIEWERS

Dr. Ralph Johnson, Quality Assurance

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APPENDIX B REQUEST FOR ANALYTICAL SUPPORT

PART 1

Performing Division: RA ***Account Number:*** **2001084**

Tasking: Verbal ***Mode (Contract-Yes/No):*** No

Acronym: **SICLUPS**

Title: Systematic Investment in Capital and Logistics for UXO Planning Study (SICLUPS)

Start Date: 17-Jan-01 ***Estimated Completion Date:*** 01-Aug-01

Requestor/Sponsor (i.e., DCSOPS): ACSIM ***Sponsor Division:*** ODEP

Resource Estimates: ***a. Estimated PSM:*** 7 ***b. Estimated Funds:*** $0.00

c. Models to be Used: **GAMS software, new model development**

Description/Abstract:

Allocation of funds for and scheduling of cleanup operations for unexploded ordnance (UXO) on a large number of present and former Army ranges to be carried out over a 6-year period are to be modeled. Prototype model and mixed-integer nonlinear programming algorithm based on this requirement are to be developed. Constraints involve annual budgets and specification of cost and duration of each of several alternative types of cleanup operations for each range. Quantity to be optimized is to be a value whose definition is flexible and which may encompass one or more of a variety of objectives pertaining to Army cost savings, health, safety, and environmental protection.

Study Director/POC Signature: ***Original Signed*** ***Phone#:*** 703-806-5679

Study Director/POC: **Dr. David Anker**

If this Request is for an External Project expected to consume 6 PSM or more, Part 2 Information is Not Required. See Chap 3 of the Project Directors' Guide for preparation of a Formal Project Directive.

PART 2

Background:

Scope:

Issues:

Milestones:

Signatures ***Division Chief Signature:*** ***Original Signed and Dated*** ***Date:***

Division Chief Concurrence:

Sponsor Signature: ***Original Signed and Dated*** ***Date:***

Sponsor Concurrence (COL/DA Div Chief/GO/SES) :

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APPENDIX C PREVIOUS RELATED WORK

Previous work in the modeling of problems in scheduling and allocation of funds for remediation of sites on current and former military installations in the framework of mathematical programming include the following: the Masters thesis by H. Goette (1996), the Masters thesis by S. Oremis (2000), and two CAA reports by L. Coblentz, Modeling to Optimize Restoration Tracking and Investments (MORTI), Report (CAA-SR-99-3) and the MORTI II Report (CAA-R-00-50). Goette and Oremis give brief reviews of the literature in the application of operations research methods to environmental management.

Although the four studies referred to above and SICLUPS are all concerned with remediation of sites on military installations and all use integer or mixed-integer programming as the basis of modeling and analysis, there are some important differences among them. The problems they treat are of different size, in terms of the number of sites and the number of years modeled. They treat problems involving various types of contamination at various categories of sites, involving various types of risks connected with this contamination, and various types of benefits. Varying amounts of detail as to model formulation and results are given in these four reports.

Types of contaminants considered can include various types of hazardous, toxic, and radiological wastes and chemical and biological contaminants in addition to UXO. Goette (1996, p. 5) considers 18 types of clean-up actions for various types of wastes. Types of sites considered are sites on active installations, sites on closed installations, Base Realignment and Closure (BRAC) sites, and FUDS. Types of risks are safety, health, and environmental. The two major types of benefits studied are risk reduction and site reuse.

When former military sites are being prepared for civilian use, there are different remediation requirements for different civilian uses, hence the cost of remediation depends on the intended land use. For example, in the case of UXO contamination, there is a requirement that all UXO be cleared down to a certain depth below the surface for most civilian land uses, and the required depth depends on the use. In planning remediation of land for civilian uses, an important question is whether only one or more than one possible future land use is to be considered.

Whether the type of site is active, BRAC, or FUDS has an effect on whether or not it makes practical sense to consider multiple options for land use for each site. Active sites are military sites that are slated to stay military, so for these there is no reason to consider multiple reuse options. BRAC sites are sites which are currently still under DoD control but which are being prepared for civilian use. Since civilian use for these sites is still in the process of being planned, it makes sense to consider several types of civilian use, and to consider remediation costs and benefits of each type. By contrast, FUDS are former DoD properties that have *already* been put to civilian use. For these, the kind of action that is needed for safety, health, and environmental protection is to a large extent already determined by the current civilian use.

What data is used in measures of effectiveness depends on how risks and benefits are modeled. Specifically, populations of various regions can be involved, but which particular population is relevant to measures of effectiveness can depend on whether risks or benefits are being considered and, in the case of risks, the type of contaminant. For chemical contaminants, there may be risks to populations some distance from the site, due to contaminants being carried by ground water, and possibly by surface water. For the risk of accidental detonation of UXO,

there is risk to any people who enter the site – one expects that people at risk would include people living in the vicinity of the site. For measuring benefits of land reuse, the population of the vicinity of the site is also appropriate to consider.

The four studies cited above and SICLUPS can all be compared and contrasted in terms of (1) the practical problems which they address, in terms of the parameters mentioned in the preceding four paragraphs, (2) the formulations of the integer programming (IP) or mixed-integer programming problems (MIP) and the description of these formulations in their reports, and (3) the analyses of results.

BAEC and related models

Goette (1996) and Oremis (2000) are concerned with remediation of BRAC sites for a wide range of contaminants. Specifically, they are concerned with 40 installations and 50 installations, respectively. Of the 18 types of action listed by Goette, only one is for UXO.

For Goette, there is an emphasis on site reuse in measuring the benefits of remediation. For each site, there are two main classes of options, one of which gives the user of the model more control over the timing of funding for the site than does the other. Within each class of options, there are specific options – different options correspond to different anticipated uses of the site following remediation. The task of remediating a site is considered as a single task – it is not sub-divided into a series of sub-tasks or phases. No particular consideration is given to the question of how much time is needed to perform a site remediation, once funding has been allocated for it.

Goette formulates a MIP model called Budget Allocation of Environmental Clean-up (BAEC), which reflects the features of the problem described in the preceding paragraph. The parameters representing the benefits of site remediations are user-defined parameters. These are indexed by the years in which funding is allocated, so that, in effect, it is assumed that if funding is allocated for a task consisting of all or a portion of a site remediation in a particular year, then that task is accomplished in that year. The *user has the freedom to assign values* at will to parameters used in computing benefits of remediation of individual sites. For one of the two main classes of options, the model has the property that **(*)** *a positive benefit will be credited even if allocations cover only a fraction of the clean-up cost*. In addition to several hard budget constraints, there are some “soft constraints” on spending, which amount to a number of additional terms in the objective function, which represent deductions from the benefit if the “soft constraints” are violated.

Oremis acknowledges that BAEC serves as a basis for the development of his models, which he names BAEC-1, CBAEC-1, BAEC-2, AND CBAEC-2. These have many of the same features described above for Goette’s model BAEC, some of which have property (*) and some of which do not.

Both Goette and Oremis gave extensive analyses of their results. With two different MIP solvers (OSL Version 2 and CPLEX 3.0) running on two different platforms, Goette (1996) reported computing times varying from 8 minutes to 100 minutes. Oremis (2000) reported computing times of under 1 minute with all four of his models.

MORTI AND MORTI II

Coblentz (1999 and 2000), in the MORTI and MORTI II projects, is concerned with clean-up of hazardous wastes at a number of sites on active installations. BRAC and FUDS are explicitly excluded from these studies. The purposes of these projects were to decide how to distribute funds for clean-ups among the major commands (MACOMs) for the years FY01 through FY14 and to plan the clean-ups so as to be in compliance with Defense Planning Guidance (DPG) requirements. The DPG requirements impose two deadlines for site remediations, an earlier one for sites designated as high-risk and a later one for the remaining sites.

MORTI and MORTI II differ from the studies by Goette and Oremis in several respects. For MORTI and MORTI II, since the sites in question are active sites, they are to remain military sites, so, as described above, there is no reason to consider multiple use options. The main criterion of value appears to be risk reduction rather than site reuse. Risk values supplied by the Army Environmental Center (AEC) are used as inputs to the models. Each site restoration is composed of up to seven phases, and a specific ordering of the phases is assumed. Consideration is given to the length of time needed to carry out these phases. Specifically, for MORTI, each phase is assumed to take 1 year, and for MORTI II, more complicated assumptions are made, stating that these lengths of time depended on cost, according to certain formulas.

The IP formulations of MORTI and MORTI II have some constraints that do not appear in the IP and MIP formulations of Goette and Oremis. There are (1) constraints for the correct ordering of the phases and the correct lengths of the phases. Since for MORTI and MORTI II, the budgets are adequate for performing all tasks, i.e., all site-phase combinations, there are (2) constraints for assuring all tasks will be done. Like the formulations of Goette and Oremis, MORTI and MORTI II have constraints pertaining to allocations to the various MACOMS, but those in MORTI and MORTI II are simpler, and to not involve the “soft constraints” in Goette and Oremis.

The objective function for MORTI and for the first IP formulation of MORTI II is a general sum of coefficients, one coefficient for each site-phase combination completed, which can depend on the year that the task is completed. In all, it has over $3300 \times 14 = 46{,}200$ unspecified coefficients. For an alternative formulation in MORTI II, the number of unspecified coefficients is reduced to $14 \times$ the number of sites, or approximately 22,000. Since these coefficients are unspecified, the *user of the model has fairly free choice in assigning values to them.* The reports state that, for specific runs of the model, values for these coefficients were chosen in a way so as to give higher priority to higher risk sites, so that higher risk sites tended to be cleaned up earlier than lower risk sites, but specific values for the coefficients were not reported. The analyses of the results appeared to demonstrate that schedules were found which achieved the sponsor’s goals for the site restorations, without explicitly reporting all parameter values in the models.

The IP formulations of MORTI and MORTI II have the property that if the model decides to begin funding for a task, i.e., a site-phase combination, in a certain year, then it must allocate funds covering the full cost of that task out of that year’s budget. The result is that all variables in the models were binary variables.

Computing times were not reported.

Comparing SICLUPS with previous work

Whereas BAEC and related models pertain to a wide range of contaminants on BRAC sites, and MORTI and MORTI II pertain to hazardous wastes on active sites, SICLUPS pertains to unexploded ordnance (UXO) on FUDS. This difference in the problems considered leads to differences in modeling.

Whereas BAEC and related models emphasize the benefits of land reuse, MORTI, MORTI II, and SICLUPS emphasize risk reduction. Whereas for BAEC and related models, multiple reuse options are considered for individual sites, for MORTI, MORTI II, and SICLUPS, there are not multiple options. For BAEC and related models, each site remediation is modeled as a single task, with no particular consideration given to the length of time needed to perform the task, but for MORTI, MORTI II, and SICLUPS, each site remediation is broken down into several phases, which must be done in the correct order, and for MORTI II and SICLUPS, allowance must be made for the possibility the a phase can extend over more than one year.

For both MORTI and MORTI II and for SICLUPS, the Army Environmental Center (AEC) provided costs estimates for all site-phase combinations, and risk estimates were given for individual sites. For MORTI and MORTI II, risk estimates were provided by AEC; for SICLUPS, a risk metric, called the Risk Assessment Code (RAC), applying specifically to UXO, is used. For SICLUPS, RAC scores for some, but not all, of the sites were obtained from USACE.

The problem being addressed by SICLUPS is different from that addressed by MORTI and MORTI II in some respects. Whereas for MORTI and MORTI II, the risks pertain to health and the environment, for SICLUPS, the risks pertain primarily to safety. The specific phases are different, and the details of actions required in these phases are different, for the two problems. The situations with respect to the Army's commitment to funding the costs of remediation are different. For the problem considered by MORTI and MORTI II, a commitment to fund full remediation on all sites in the model appears to have been made, and there is Defense Planning Guidance giving deadlines. For SICLUPS, there is as yet no such commitment. This appears to be due largely to the estimated costs involved: the number of sites potentially eligible for the DERP-FUDS program is large, and remediation costs for UXO are expected to be high. There is a strong possibility that there will *not* be adequate funding for all sites.

Similarities and differences of the approach taken in SICLUPS, compared to that taken in MORTI and MORTI II, correspond to similarities and differences in the problems addressed. The MIP formulation for SICLUPS is similar to the IP formulations for MORTI II in some basic respects: for both models, decision variables are in triple-indexed arrays, with the first index for the site, the second index for the phase, and the third index for periods of time, and there are constraints which enforce the correct ordering of the phases.

However, the two models have different rules for funding allocation. For MORTI and MORTI II, if the model decides to begin funding for a task, i.e., a site-phase combination, in a certain year, then it must allocate funds covering the full cost of that task out of that year's budget, even if the task is expected to take several years to accomplish. This rule was not considered either necessary or realistic for the UXO problem addressed by SICLUPS. For

SICLUPS, there is more flexibility in funding. Specifically, the 3rd phase, the remedial action phase, tends to be very costly, and it was not considered reasonable to require that all of the funding for this phase for a given site be supplied from one year's budget. Likewise, the 1st phase actually consists of several steps, and it was considered more reasonable to spread the cost of this phase over 2 years.

This difference in rules for funding allocation results in a difference in the decision variables for the two types of models. For SICLUPS, the most basic decision variable is a continuous-valued variable, giving, for each ordered triple representing a combination of a site, a phase, and a time period, the fraction of the task funded from the budget for this time period, where the task is the site-phase combination. Then there are also binary variables, which are needed to write the constraints needed for the correct ordering of the phases. Since the SICLUPS linear programming model involves both continuous-valued and binary decision variables, it is a mixed-integer programming (MIP) model.

For SICLUPS, since costs are so high, one cannot assume that there is anything near adequate funding for all phases of remediation for all sites, so there cannot be any constraint such as that in MORTI II which states that all of these will be done. Since FUDS are former, not current, DoD sites, they are not associated with MACOMs, and so it would not make sense to apply restrictions pertaining to MACOMs. Although these sites are associated with USACE divisions and with districts within divisions, the analysts working on SICLUPS saw no reason to apply restrictions pertaining to divisions or districts either.

Since with SICLUPS, there is the possibility of performing some or parts of some phases of remediation of a site without completing all phases, there is the question of what value to attribute to doing only a partial site remediation. Since there is no assurance that risk from UXO has been entirely removed until the remedial action phase is complete, SICLUPS awards *no value* to doing only a *partial* site remediation. In this respect, as in a number of other respects, SICLUPS differs from BAEC and related models, as indicated by statement **(*)** in the section "BAEC and related models" above.

Since the type of risk SICLUPS deals with is qualitatively different from that which MORTI and MORTI II deal with, SICLUPS models this risk differently. Since for the risk of injury due to UXO detonation, the people subjected to the risk are those who enter the site, it is inferred that those living in the vicinity of the site are particularly at risk. For this reason, the risk metric given by the RAC score was modified by adding a term representing this local population. The objective function for SICLUPS, in contrast to those for MORTI and MORTI II, is given by an explicit formula involving the modified risk metric, site acreage, and only a *small number of user-defined parameters*.

For SICLUPS, the range of values of some of the key parameters in the objective function for which the analysts on the project were able to find solutions was explored. Moreover, the dependence of computing times on these values was studied in some detail. These results are summarized in Appendix G.

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APPENDIX D DATA COLLECTION

The collection of information about sites being considered for UXO remediation, about remediation procedures, and about the numbering systems used by USACE and AEC for identifying FUDS properties and parts of these properties, is reported in this Appendix.

Data collection for the SICLUPS project involved a workshop held at the Center for Army Analysis (CAA), followed up by requests for information from points of contact at the various organizations involved, with whom CAA analysts made acquaintance at the workshop, and obtaining information from the U. S. Army Corps of Engineers (USACE) website, whose address at the time of this writing is

http://www.usace.army.mil/.

Some of the requests for information took the form of face-to-face meetings with people at the various organizations involved.

CAA workshop to discuss development of UXO model and information obtained in follow-up

The CAA Workshop to Discuss Development of UXO Prioritization Model took place at CAA on March 15, 2001. Attending were representatives from:

(1) the Ordnance and Explosives Center of Expertise (MCX) and Design Center of the U.S. Army Engineering and Support Center, Huntsville, AL, of the U.S. Army Corps of Engineers (USACE),
(2) the Army Environmental Center, Aberdeen Proving Ground, MD, also under ACSIM, and
(3) the Resource Analysis (RA) Division of CAA.

At this workshop, CAA analysts working on the SICLUPS project learned about:

(1) the inventory of Army ranges being developed at the Army Environmental Center (AEC), which includes active, inactive, closing, and closed Army Installations
(2) the Defense Environmental Restoration Program (DERP) for active, inactive, BRAC, and FUDS
(3) the overall responsibility of authorities at USACE, Huntsville for identifying FUDS potentially eligible for funding for environmental restoration under the DERP-FUDS program and for designing and overseeing the process of environmental remediation at all FUDS,
(4) the Risk Assessment Code (RAC), a risk metric for hazards to safety, health, and the environment posed by UXO, which was developed by USACE, Huntsville and which has been calculated for some FUDS,
(5) the availability of names of some sites eligible for the DERP-FUDS program and RAC scores for some of these sites on the USACE website, and
(6) the Remedial Action Cost Engineering Requirements (RACER) model for estimating the costs of the various phases of environmental remediation of sites contaminated by

UXO.

The point of contact from MCX emphasized that the RAC score of a site is very susceptible to change. He said that the RAC scores posted on the USACE website were not always the most up-to-date scores and agreed to send to the CAA project analysts up-to-date RAC scores for 100 FUDS. The point of contact from AEC agreed to send information on the inventory of FUDS – specifically those FUDS for which the AEC had estimated, via the RACER model, remediation costs for UXO contamination.

The MCX point of contact sent not only RAC scores for 100 sites, as promised, but also the complete scoring cards with the details of on how these scores were calculated, in hardcopy. Each of these sites was either in Florida or California – it appeared to be in these two states that the greatest efforts were made to maintain up-to-date RAC scores. The AEC point of contact sent a file with a list of RACER cost estimates for remediation of UXO hazards for 1,127 Army FUDS, as promised, and also sent information on the sizes of these sites, in numbers of acres, in hardcopy. The cost estimates were based on the assumption that remediation consisted of three phases: (1) the study phase, (2) remedial design, and (3) remedial action. For each site, a complete set of cost estimates would consist of three estimated costs for each phase: the expected cost, the worst case (highest) cost, and the best case (lowest) cost.

USACE has a numbering system for sites which it identifies as FUDS properties. Each such property is designated by an alphanumeric string, consisting of (1) a letter, followed by (2) a 2-digit number, followed by (3) a 2-letter abbreviation for the state containing the site, followed by (4) a 4-digit number. For the purposes of cost estimation, AEC has sub-divided each of these properties into one or more sub-sites. AEC's identifier for a sub-site of a FUDS property consists of the USACE-determined property identifier, followed by a string of the form

"xx-A-xx",

where the first "xx" consists of two digits (of which either or both may be '0') and the second "xx" is either empty or consists of either one or two digits. Both the cost estimates and the acreage data received from AEC conformed to this system of sub-division of USACE-determined properties into sub-sites.

Of the two data lists obtained from AEC, that with the acreage data is more complete. There are a number of instances of USACE-determined FUDS properties for which cost estimates were available for some, but not all, AEC-determined sub-sites.

Descriptions of FUDS properties on the USACE website sometimes made references to sub-divisions of properties. However, these sub-divisions did not generally conform to AEC's system of sub-divisions. For example, the website entry for the FUDS property in Franklin County, FL whose USACE identifier is I04FL0124 described various sub-sites, each identified by a single letter, partly in terms of terrain and vegetation and partly in terms of uses being made of the areas – there were beachfront areas, where were wooded areas inland from the beach, and there were areas with trailer parks. But CAA analysts were not able to precisely correlate specific USACE-defined sub-divisions of this site with specific AEC-defined sub-sites of the site.

Certain limitations on the available information on RAC scores became evident. Of the 126 sites in the full-sized model developed for this project, all located in Florida and California,

most had RAC scores on the hardcopy forms sent by our point of contact at MCX. Of the remaining sites, RAC scores for some were listed on the USACE website. It was uncertain how up-to-date the scores from the website were. Finally, there were sites for which no RAC score was available from either source. Some of the 126 sites in the SICLUPS model consisted of only part of a USACE-determined FUDS property. For these cases, the SICLUPS model assigned to each sub-site the RAC score for the USACE-determined FUDS property of which it was a part. The accuracy of this way of assigning of RAC scores to sub-site is questionable, but there did not seem to be any better way of making the assignment from the information available.

Conceivably, if the procedure for computing the RAC score were to be changed to give more detailed information on the RAC scoring sheets, there might be a more accurate way to assign RAC scores to sub-sites. For example, more detailed information could be entered on where various pieces of UXO were discovered, or more precise information about the location of roads or buildings in relation to various sub-sites of a FUDS property could be supplied.

Documents on the USACE website describing remediation procedures

A number of engineer manuals and pamphlets were found on the USACE website, describing the remediation process. These included Engineer Pamphlet 1110-1-18, dated 24 April 2000, entitled “Ordnance and Explosives Response”. This pamphlet gives an overview of ordnance and explosive remediation programs, beginning with an overview of their legal and regulatory bases, a description of what organizations have responsibility for what parts of the process, and, over several chapters, a detailed description the procedure to be followed in the remediation process, as determined by law, regulations, and USACE policy. There are three types of removal actions: emergency, time critical, and non-time critical. Figure 5-2 on page 5-6 of that pamphlet gives a flowchart for the steps in the non-time critical removal action (NTCRA) process. The phases of remediation for a NTCRA described in the pamphlet are similar to those described above in connection with the file of cost estimates, but in place of the study phase is the following list of steps:

1. preliminary assessment of eligibility (PAE) – ending with issuing of the Inventory Project Report (INPR)
2. site inspection – ending with issuing of the Archive Search Report (ASR)
3. engineering evaluation / cost analysis (EE/CA) approval memorandum
4. engineering evaluation / cost analysis (EE/CA) – ending with an EE/CA Report
5. action memorandum.

The chapter on the EE/CA emphasizes provisions to facilitate public participation in this phase.

Another pamphlet on the website is Engineer Pamphlet 1110-3-8, dated 1 December 1999, entitled “Engineering and Design – Public Participation in the Defense Environmental Restoration Program (DERP) for Formerly Used Defense Sites (FUDS)” discusses the requirements for facilitating public participation in the process of planning site remediations. This involves the establishment, under certain conditions, of Restoration Advisory Boards (RABs), which are to have members representing various groups of concerned people, called stakeholders, from government and private organizations.

Tutorial on the RACER cost model

CAA analysts on the SICLUPS project attended a tutorial on the Remedial Action Cost Estimation Requirements (RACER) model given by a visitor from USACE, Omaha, NB at the Office of the Directorate for Environmental Programs (ODEP). The tutorial was also attended by people from ODEP and from the Environmental Division of USACE. RACER was the model used by AEC for the cost estimates they supplied for the SICLUPS project, described above.

The CAA analysts also received copies of the RACER software itself. However, this software required much more detailed information about the sites as inputs than the analysts at CAA were able to obtain.

Visit to personnel at the Environmental Division of USACE

CAA analysts on the SICLUPS project visited people at the Environmental Division of USACE, in the Pulaski Building, in Washington, DC. They obtained an overview of the process of prioritization of sites and funding for their remediation, for the entire DERP-FUDS program. It was made clear that the three categories of remediation in DERP-FUDS were competing with each other for funding. At the time of that visit, funding for remediation against UXO was limited to $40M per year. One reason given for this limit was that there was Defense Planning Guidance for remediation of hazardous, toxic, and radioactive waste (HTRW) but not for UXO.

The visiting CAA analysts were given a brief description of the site prioritization process for the DERP-FUDS program. Prioritization was first on the basis of RAC score, then, for prioritization among sites with equal RAC scores, there were subjective evaluations on the part of people at various levels. People at the District level prioritized sites in their districts, and the results were sent to the Division level. People at each Division level considered all the prioritized lists from their District offices, and combined them into one large prioritized list, using their judgment on how to prioritize sites having the same RAC score from different districts. Then people at the USACE headquarters level would similarly combine all the prioritized lists from the respective Division offices. Following this, on the basis of the full-sized prioritized list, decisions would be made at the USACE headquarters level on how much funding to give to each Division. Then, when each Division office obtained its funding, it would decide how to divide that funding among its District offices.

The people in the Environmental Division said that they had software that would take a prioritized list as input and determine the scheduling and funding of site remediations. Because of the high costs involved in UXO remediation, this schedule stretches for approximately a century into the future. The schedule was considered tentative, since it is impossible to predict costs accurately far into the future.

Visit to the Baltimore District Office of the North Atlantic Division

CAA analysts on the SICLUPS project then visited people at the Baltimore District Office of the North Atlantic Division of USACE to learn the point of view of the people who seem to be the USACE decision-makers closest to the actual sites to be remediated; that is, closest not only geographically but also in terms of the degree of detail with which they have studied the sites. It appears that the prioritized list which the people at the District level choose for sites in their districts, described above as part of the USACE-headquarters lead process for

determining funding, is not something they are required to adhere to rigidly. They appear to have a wide range of choices for scheduling their projects, within their funding limits.

The Baltimore District covers Washington, DC, most of Maryland, most of the central mountainous region of Pennsylvania, some of the Allegheny Plateau area of central New York State and a small part of Northern Virginia. The Baltimore District people had a long list of sites that they wished to remediate, but for lack of funding, they had no basis for predicting any schedule for most sites. Their work involved remediation of active sites as well as FUDS.

A site will be given priority if it is designated a “time critical” removal site.

In describing the procedures they generally follow, the people in the Baltimore District Office mentioned a number of instances in which a reaching a decision or approval of a document involves consultation among two or more groups. The decision to designate a site for time critical removal is made by the Division Office in consultation with the authorities at the Engineering and Support Center (USAESCH) in Huntsville. Although Inventory Project Reports (INPRs) are written at the District level, copies are sent to Division Offices and to Huntsville. For Archive Search Reports (ASRs), the District does a draft report, which is reviewed by Huntsville. Copies of final ASRs are sent to a number of agencies and stakeholders, including regional EPA offices, state governments, and property owners. The ASR for a site may either confirm its RAC score or revise it, but revisions of the RAC score are reviewed by a technical advisory board. The Decision Document is the administrative result of an EE/CA written at the District level in consultation with Huntsville and is typically released 6 months after the EE/CA is completed.

The people in the Baltimore District Office emphasized that the consultation and reporting processes, as well as the need to give stakeholders time to respond to decisions and documents, had the effect of substantially increasing the length of time needed for remediation and made this length of time difficult to predict. Specifically, the requirement for the involvement by the authorities in Huntsville in certain steps of the remediation process for each and every site in the DERP-FUDS program meant delays whose lengths were difficult to predict.

Apart from these delays, the people in the Baltimore District Office were able to give rough estimates of lengths of time needed for certain steps for certain cases, based on their experience. They said that for Tobyhanna sites, the PAE step and the development of the INPR took about 6 months to a year, but that review of draft INPRs by the State of Pennsylvania could cause delays. The EE/CA process would typically take from 6 months to 2 years. Remedial design would typically require about 6 months to establish a contract and about 6 months for the contract work to be performed.

They said that since the remedial action phase of a site remediation is typically expensive and labor intensive, they have often found it to be practical to fund it piecemeal over a number of years.

Because of funding limitations, work on earlier phases of some of the lower priority sites was also sometimes piecemeal. For example, one year they found that they had about $250,000 remaining after committing funds to top priority work. They used the remainder for investigating more anomalies at the Camp Simms site.

The foregoing inquiries, together with collection of more data from open sources, provided adequate data for the SICLUPS models to be developed as well as an idea of what assumptions would be needed for the model and insights on issues related to these assumptions.

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APPENDIX E COMPLICATIONS IN PROCEDURES THAT IMPACT MODEL VALIDITY

A major difficulty in formulating an appropriate integer programming (IP) or mixed-integer programming (MIP) model for UXO remediation, based on available information, was the difficulty in *predicting lengths of time needed* for the various phases of remediation. This came out very clearly in interviews with people in the Baltimore District Office of the USACE, described in Appendix D. This uncertainty applies particularly to phase 1, the study phase. Procedures stipulated by USACE documents require that the study phase consist of several steps. These steps were outlined in Appendix D in the section on “Documents on the website describing remediation procedures”. There is uncertainty about both the lengths of time needed for the individual steps within phase 1 and delay times between these steps. By comparison, phase 2, the remedial design phase, is considered to be fairly short, and phase 3, the remedial action phase, fairly straightforward in terms of the procedures to be followed. It appears that, by the time the site remediation project has reached phase 3, the actual remediation procedures have been decided on, and the speed at which they can actually be carried out has thus far been limited mainly by the availability of funding.

One might expect there to be one list of steps, with a definite linear time ordering, to be applied unconditionally to all sites. The reality of these procedures is far more complex. The first complicating factor is that there are 3 types of removals: emergency, time critical, and non-time critical. The procedures are different for these 3 cases. Moreover, the structure of the steps for each type of removal is not a simple linear ordering – it is more like a flowchart or a graph, with decision points and branching, where the branch to be taken at the end of a step may depend on discoveries made during that step. If work on a site starts out as a non-time critical removal (NTCRA), there is the possibility that a discovery made during a step in the flowchart for NTCRAs will force a re-evaluation of the type of removal - a non-time critical removal may be reclassified as a time critical removal.

Thus, at the outset of work on a specific site, the number and ordering of the steps that this work will go through is not definitely known. The various steps in the study phase require consultation among two or more agencies, and each agency has its own procedures, its own workload, its own resources for dealing with this workload, and its own priorities. For certain steps, the central authority in Huntsville must be involved, but the central authority has responsibility for *all* of the sites in the DERP-FUDS program, in contrast to a District office, which has responsibility only for the sites in its own district. For these steps, then, the *length of time needed to perform the step* for a given site *may depend on certain factors totally unrelated to the characteristics of the site* in question.

In general, limitations in available resources may have the effect of limiting the number of sites for which phase 1 or phase 2 can be done in a given time segment. This applies particularly to human resources, i.e., *limits on the number of people* with the requisite knowledge and experience for certain tasks – for example, for making decisions in the Huntsville office and for performing specialized engineering work in phases 1 and 2 of remediation.

If there is a requirement that, at certain points in the planning process, stakeholders be provided with copies of certain documents and be given at least a certain length of time to examine these documents and to reply with their comments before the next step in the

remediation procedure is taken, then this requirement may substantially affect the lengths of time involved, time not only for certain steps but also time between steps.

Modifications of the basic SICLUPS model are described in Appendix G. Specifically, models of Type A and Type B are described there. Models of Type B have constraints representing limits on the number of sites for which phase 1 or phase 2 can be done in a given time segment. Options for refinement of the schedule at the time segment level to a schedule at the year-by-year level are described in Appendix K. The rules of allocation for some of these options contain a requirement that there be a gap of at least one year between the end of phase 1 and the beginning of phase 2. One of the reasons for this requirement is the need for stakeholder involvement in the remediation process.

APPENDIX F EFFECTS OF DEMOGRAPHICS ON VALUE

The definition of value, introduced in Chapter 2 and used in the objective function of the MIP formulation of the SICLUPS models, treats sites in Florida differently from those in California. This difference is based on the following reasoning: In Florida, there are two regions that attract people strongly, namely, the beach areas and the Orlando area. Risk is increased by the fact that some FUDS properties in Florida believed to have UXO contain beach area, because they were used for training in amphibious operations. It is to be expected that people, both Florida inhabitants and visitors to the state, will often cross a county line on their way to visiting either a beach or one of the attractions in the Orlando area. For this reason, parameters used as indicators for local population include, not only the population of the county containing the site s, but also the sum $Pnbrco_s$ of populations of all counties in Florida that border on this county.

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APPENDIX G COMPARING COMPUTING TIMES OF SEVERAL MODELS

Two modifications of the basic SICLUPS model that was introduced in Chapters 2 and 3 were developed, and computing times for the optimizations were compared for the 3 models.

The first modification of the basic SICLUPS model involved reducing the size of the set of sites from 126 sites to 108 sites. This was done by deleting 18 of the sites, located in the Los Angeles District, from the original model. Some of these sites were of small size (at most 4 acres) and some were in very remote desert locations. For this first modification, there were no changes to the basic model other than for the sites. Since the first modified model has exactly the same GAMS formulations for the objective function and for the constraints as the basic model, both were called Type A models.

The second modification of the basic SICLUPS model kept the same 126 sites as the basic model, but involved adding two more parameters, LIMPH1 and LIMPH2, and two more constraints, as follows:

$$\sum_{s} I_{s,1,t} \leq \text{LIMPH1}, \forall t$$

$$\sum_{s} I_{s,2,t} \leq \text{LIMPH2}, \forall t,$$

where the summation is over all 126 sites in the model. This model was called the Type B model.

SICLUPS optimization programs for the two modified models were written, and computing times for the basic SICLUPS model and the two modified models for runs on an IBM RISC/6000 (Model 590, Type 7013), with various combinations of parameter values, were studied. All of the runs for which results are reported in this Appendix were fully successful, where "fully successful" is defined in Appendix J.

Outcomes of Computer Runs of Models of Type A. A strong dependence of computing time on model size and on the values of W_{RAC}, W_{copop}, and the ratio R defined by

$$R = \sum_{t} b(t) \Big/ \sum_{s} \sum_{p} \text{COST}(s,p),$$

where the summations are over all time segments, all sites, and all phases, respectively, was consistently observed. (R gives an upper bound on the fractional part of the total remediation that is possible to complete.) It was generally found that as R decreased, computing time increased substantially.

For cases with $R \leq 0.5$, computing times were often prohibitively long for values W_{copop} = 5, 10, or 20 combined with positive values for W_{RAC}. It was found, however, that for several values of $R \leq 0.5$ with $W_{copop} = 100$, computing times were reasonable for W_{RAC} = 1 or 2, and, in some cases, for $W_{RAC} = 5$. Results of runs for the original 126-site model for $W_{copop} = 100$, for ranges of values for W_{RAC} and R, are given in Table 1 of Figure G-1. In Figures G-1 through G-3, the weighting factor W_{RAC} is called RACWT and the weighting factor W_{copop} is called COPOPWT. The computation failed with $W_{RAC} = 0$ when R was reduced further to R = 0.443. The effect of model size can be seen by comparing these results to those for the somewhat smaller 108-site model, where less computing time was needed for two cases with R = 0.554, and the computation succeeded for one case with R = 0.443, as shown in Table 2 of Figure G-1. One can see that deleting 18 sites from the larger model can have the effect of substantially reducing computing time and can make the difference between success and failure of a computer run.

Outcomes of Computer Runs of Models of Type B. Values of the additional parameters chosen for test runs of Type B models were as follows:

LIMPH1 = 30

LIMPH2 = 30.

As with Type A models, a strong dependence of computing time on values of W_{RAC} and R was observed. For R values greater than 1, it was found that runs with moderate computing times were possible for values of W_{RAC} up to 200 or 300. In fact, for some R values, there appeared to be somewhat of a trend for computing times to decrease with increasing W_{RAC}. Results of runs with for $W_{copop} = 100$, for ranges of values for W_{RAC} and R, are given in Figure G-2.

Comparing computing times for the two types of models. Although computing times for both Type A and Type B models were often found to be moderate for R values near and above 1, they tended to be shorter for Type B models than for Type A models. A direct comparison was made for R = 1.125 for several values of W_{RAC} up to 100; these are shown in Figure G-3. There, one can see that for cases with $W_{RAC} > 0$, changing from a Type A model to a Type B model reduces computing time by a factor better than 2.

It is of practical interest to be able to run models for large values of W_{RAC} efficiently, since W_{RAC} represents the degree of emphasis that the user places on risk as measured by the RAC score in the definition of the objective function for the MIP problem. Thus the user of the SICLUPS methodology who chooses to measure risk primarily or exclusively on the basis of the RAC score would want to choose a large value of W_{RAC}.

Historical comparisons. Historical background information on well-known case studies, relating computing times to the number of binary variables for some binary integer programming (BIP) problems is given by Hillier and Lieberman (1995), pages 533-534.

Table 1. Computing times for Type A Models
For fully successful runs of the 126-site model with COPOPWT=100,
for various values of R and RACWT.

R: / RACWT:	5	1.5	1.125	1	0.5	0.665	0.554
0	3.53min.	33.7min.	19.6min.	41.7min.	6hrs.,4.6min.	6hrs.,3.8min.	2hrs.,25min.
1	3.58min.	14.2min.	1hr.,51.8min.	2hrs.,12min.	7hrs.,56.3min.	10hrs.,41.8min.	12hrs.,3.9min.
2	3.71min.	17.4min.	23.3min.	2hrs.,39.2min.	7hrs.,38min.	13hrs.,6min.	1hr.,52.4min.

Table 2. Computing times for Type A Models

For fully successful runs of the 108-site model
with COPOPWT=100, for a few values of R
and RACWT

R: / RACWT:	0.554	0.443
1	57.5min.	4hrs.,36.9min.
2	6 hrs.,19.9min.	

Figure G-1. Computing times for Type A models.

Table 3. Computing times for Type B Models

For fully successful runs of the 126-site model with COPOPWT=100, for various values of R and RACWT

R: / RACWT:	1.5	1.25	1.125
0	18.0min.	1hr.,12.9min.	2hrs.,32.2min.
5	15.2min.	2hrs.,54.6min.	46.7min.
10	14.9min.	1hr.,13.8min.	22.7min.
50	13.5min.	1hr.,13.2min.	19.8min.
100	14.6min.	15.6min.	34.8min.
200	13.7min.	20.3min.	22.3min.

Figure G-2. Computing times for Type B models

Table 4. Comparing computing times for the two Types of Models

For fully successful runs of the 126-site models with
COPOPWT=100, R=1.125, and various values of RACWT

RACWT:	0	5	10	20	50	100
Model type:						
Type A	19.6min.	1hr.,48.6min.	7hrs.	30min.	1hr.,49.4min.	1hr.,12.5min.
Type B	2hrs.,32.1min.	46.7min.	22.7min.	18.2min.	19.8min.	34.8min.

Figure G-3. Comparing computing times for Type A and Type B models

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APPENDIX H OUTPUTS OF THE OPTIMIZATION PROGRAM

Two types of models, Type A models and Type B models, were defined in Appendix G. For both types of model, the optimization program has an output file designed to be read by humans. This human-readable file has three sections, as follows:

1. Echo of input parameters. The parameters echoed are:
   a. all model parameters other than data inputs,
   b. budgets, b_t, for all $t \in T$,
   c. costs, $c_{s,p}$, for all $s \in S$, $p \in P$, where S is the set of sites of the model and P is the set of the three phases of remediation.

2. A site-by-site display of the optimal schedule of remediations, determined by the computed optimal values of the decision variables, which were introduced in Section 3.3. Specifically, for each site s, two matrices, each of dimensions 3×6.
   The first matrix gives values of $delf_{s,p,t}$, defined by

$$delf_{s,p,t} = a_{s,p,t}/c_{s,p};$$

   the second matrix gives values of $a_{s,p,t}$.
   The quantity $delf_{s,p,t}$ represents the fraction of the remediation task indexed by (s,p) that is accomplished in time segment t, defined in terms of cost.
   The (p,t) entry of the matrix, that is, the entry in row p and column t, gives $delf_{s,p,t}$ or $a_{s,p,t}$, for each $p \in P$, $t \in T$, where T is the set of 6 time segments in the model.

3. A summary of results:
   a. For each time segment $t \in T$, the total amount allocated during t:
   $\sum_s \sum_p a_{s,p,t}$, summed over all $s \in S$, $p \in P$.
   b. A table summarizing results for the 3rd phase of remediation, remedial action, which has generally been estimated to be the most expensive of the three phases. The table has a row for each site $s \in S$ and 8 columns. The first six columns represent the time segments $t \in T$. For each ordered pair (s,t), the corresponding table entry is either 0 or 1; it will be 1 if and only if remedial action work is being done for this site during this time segment, i.e., if and only

if $a_{s,3,t}$ is positive (or equivalently, if and only if $delf_{s,3,t}$ is positive).
In the 7th column, the entry for each site s tells what total fraction of the remedial action is done:

$$\sum_t delf_{s,3,t} \text{ , summed over all } t \in T.$$

In the 8th column, the entry for each site s is either 0 or 1; it will be 1 if and only if remedial action for the site is complete by the end of the last time segment.

For models of type A, the optimization program has a second output file, which serves as input to the post-processing program. The post-processing program, code_stats, is described in Sections 4.2 and 4.3, and input and outputs to code_stats are described in Appendix I.

APPENDIX I INPUTS AND OUTPUTS OF THE POST-PROCESSOR

The Army manager who applies the SICLUPS methodology to a given set of sites and who wishes to examine many possible remediation schedules can perform multiple runs of the SICLUPS optimization program. Different runs can have different *combinations of values* for the parameters appearing in the VALUE function, namely the weighting factors introduced in Chapter 2 and the parameter VALDISCT. The managers can do an analysis comparing the results for these different combinations of parameter values, and choose parameters according to which of the resulting schedules they prefer. The post-processing program, “code_stats”, is a tool that can be used to facilitate this analysis. An example of such an analysis was described in Section 4.3.

The post-processing program, “code_stats”, takes the 2nd output file of a run of the SICLUPS optimization program, called the “-.OPTVALS” file, and computes and outputs various statistics for the run. The post-processing program has a runtime of at most only a few seconds.

Inputs to the post-processing program: To run “code_stats”, the user must first edit the 2nd output file of the optimization program, making the following two changes:

(1) inputting an asterisk “*” in the first column of each of the first 6 non-blank lines. The first of these non-blank lines reads:

“GAMS implementation of optimization code for the UXO problem”;

.......the second gives the date and time of the run of the optimization code; each of the 3rd through 6th lines gives a parameter value, the last being RACWT.

(2) deleting the periods in all occurrences of “A.L” and “E.L”.

Assuming the name of the run of the optimization code is a character string which is referred to here by the name *prefix,* so that the “-.OPTVALS” file has the name

prefix.OPTVALS,

then the user must fill in the following items in the GAMS source code for “code_stats” near the beginning of that code:

(1) in the GAMS preprocessor statement

$INCLUDE .OPTVALS

prefix must be entered immediately before the string ".OPTVALS" ;

(2) in the statement

runname = ;

the user must choose either a number or a quoted character string, which will be referred to here as *runname* following the = sign.

Output of the post-processing program: The program code_stats" creates and writes to an output file called

cumstats

representing various cumulative statistics which are relevant to the Army UXO program goals listed in Section1.2. Here, "cumulative" means cumulative over the six time segments. These are quantities derived from the computed optimal values for the variables $E_{s,p,t}$ and $a_{s,p,t}$, $s \in S$, $p \in P$, $t \in T$, where S is the set of sites, P is the set of the 3 phases of remediation, and T is the set of 6 time segments in the model.. The output consists of a header line followed by 8 blocks of statistics. The header line reads

" +++++++ CUMULATIVE STATISTICS FOR RUN *runname* +++++++" .

Each block consists of a title followed by a 4×6 matrix. The title describes the quantity whose values are given in the matrix. The rows of the matrix are labeled, in order ALL, FL, SAC, LA, representing, respectively, the total value of the statistic for all sites of the model, and the values of the statistic for each of the three geographic areas of the model. For example, the first block represents expenditures. Thus, in the first row of the matrix in this block, the j^{th} entry represents the total of all expenditures, which is the sum over all ordered pairs (s,p) of costs $c_{s,p}$ such that phase p of remediation of site s has been completed by the end of the j^{th} time segment, $s \in S$, $p \in P$. Each subsequent row gives the corresponding information for the appropriate geographic region, i.e., again a sum of costs, but now summed only over all sites s in this region. For all 8 of

the blocks, because the quantities are cumulative over time, the entries in any given row form a non-decreasing series. The 8 headings are as follows:

1. Expenditures
2. Acres cleared
3. Acres cleared per million dollars spent in category
4. Acres cleared on sites with RAC scores = 1
5. Acres cleared on sites with RAC scores = 2
6. Florida acreages --- details
7. Sacramento and San Francisco Districts acreages --- details
8. Los Angeles District acreages --- details.

The quantities in the last 3 blocks give a further breakdown of numbers of acres cleared, a block for each of the 3 main geographic areas, with statistics given for 3 sub-areas, for each block. For each of the two main areas in California, the 3 sub-areas partition the main area. That is, each site in the Sacramento and San Francisco Districts in the full 126-site SICLUPS model belongs to exactly one of the following sub-areas:

North
South
Bay.

Likewise, each site in the Los Angeles District in the full 126-site SICLUPS model belongs to exactly one of the following sub-areas:

Coastal high population density (CSTHI)
Coastal low population density (CSTLO)
Inland.

By contrast, the 2 sub-areas

Beach
Interior (INTER)

partition Florida, i.e., each site in Florida in the full 126-site SICLUPS model belongs either to "Beach" or "Interior" but not to both. The 3rd sub-area

Orlando area (ORLANDO),

which contains sites only in Orange County, is contained in the sub-area "Interior". The precise definitions of all 9 sub-areas are in terms of counties and are given in Figure 1, in Chapter 1.

Note on conditions for post-processing for the two types of models: The two general types of SICLUPS models, Type A and Type B, were described in Appendix G. In their present configurations, the optimization program for Type A models outputs the 2nd output file, called "-.OPTVALS", described in this Appendix, but the optimization program for Type B models does not. However, the optimization program for Type B models could easily be modified to produce the "-.OPTVALS" file. The user is advised to consider the disk space which may be used if a large number of runs is made of an optimization program producing the "-.OPTVALS" file.

APPENDIX J   SOFTWARE AND HARDWARE SYSTEMS USED

The SICLUPS optimization programs (or simply optimization programs) for this project were developed using the Generalized Algebraic Modeling System (GAMS) and implemented via the GAMS/OSL software on the IBM RISC/6000 (Model 590, Type 7013) machines at the Center for Army Analysis (CAA). The optimization programs were written in the GAMS language. Thus GAMS and OSL are software systems that were used as *tools in the development of the computer programs* in the SICLUPS project.

GAMS and OSL are *commercially available* software systems *for general mathematical programming problems*, which were used in the development of the SICLUPS models. GAMS is front-end software which provides the user a convenient way to set up large and complex data structures which are needed for input to solvers. Solvers are the computer programs that actually solve the mathematical programming problems. Thus the GAMS system is potentially applicable to any of the major types of mathematical programming: to both linear and non-linear programming, to continuous-variable, integer (IP), and mixed-integer (MIP) programming. Since SICLUPS models are formulated as mixed-integer linear programming (MIP) problems, a GAMS implementation of a SICLUPS model needs to call a MIP solver. For the GAMS/OSL software at the Center for Army Analysis, the GAMS "SOLVE" statement calls the IBM Optimization Software Library (OSL) mixed-integer linear programming (MIP) solver.

Possible outcomes of a run of an optimization program implemented via GAMS/OSL

As far as success or failure of a computer run is concerned, there are 3 possible outcomes:

(1) fully successful: a solution has been found for which all decision variables are of the required type (i.e., for SICLUPS models, for which variables $I_{s,p,t}$ and $E_{s,p,t}$ have binary values and $a_{s,p,t}$ have non-negative values, for all $s \in S$, $p \in P$, $t \in T$) and which comes within the "termination tolerance" of being optimal; that is, the solution's objective value has been found by the code to be within 100**optcr* per cent of the best possible solution, where *"optcr"* is one of the OSL parameters, introduced below;

(2) partially successful: a solution has been found for which all decision variables are of the required type but which does not come within the "termination tolerance" of being optimal;

(3) failed: no solution has been found for which all decision variables are of the required type.

The GAMS/OSL software system reports one of these three outcomes to the computer terminal at the end of the run. *All of the runs for which results are described in Appendix G were fully successful.*

In general, in the course of the development of optimization programs in the course of the SICLUPS project, the most common diagnostic connected with partial or complete failure of runs was that computing time exceeded the maximum allowed time, specified by the OSL

parameter, *reslim,* defined below. In one instance, the listing file for the run appeared to indicate that there was not sufficient random access memory (RAM) for all of the nodes in the branch-and-bound tree for the MIP problem.

Selection of OSL parameters for runs of optimization programs in SICLUPS

Since the GAMS code calls the solver OSL to actually solve the mixed-integer linear programming (MIP) problem, the GAMS code must pass to OSL any values of parameters to be used in the MIP solution algorithm that are not the default values for these parameters. These parameters, called OSL parameters, are listed and explained in the GAMS publication “GAMS – The Solver Manuals”.

In the development of the optimization programs in the SICLUPS project, the default values of most OSL parameters were found to be adequate. The only exceptions were as follows:

iterlim – the iteration limit, the limit on the number of iterations of the OSL branch-and-bound solver,

reslim - the resource limit, the limit on the amount of CPU processing time, in seconds, and

optcr - the relative optimality criterion.

A large value of *iterlim* such as 7000000 was generally chosen, so that actual computing time for a given run would be bounded by *reslim* . For the larger models, reslim was typically set at values equivalent to 15, 20, or 50 hours. For *optcr*, the value of 0.15 was sometimes chosen in place of the default value of 0.10.

For a few runs, experiments were made with one more exception to the use of default values – for the parameter *method*, which determines the basic method of solution of the continuous-variable linear programming problem that arises at each node of the branch-and-bound tree of the mixed-integer linear programming problem. Of several possible values for *method*, the default value is *psimplex*, for the primal simplex method. For SICLUPS, use of one of the interior-point solvers instead of the simplex method was occasionally tried. The interior-point solver was not found to give any advantage, however, either with regard to speed or accuracy of solutions, and the default value, *psimplex*, for *method* was used in all computer runs for which outputs are reported here.

APPENDIX K REFINEMENT OF THE SCHEDULE TO THE YEAR-BY-YEAR LEVEL

Reasons for having two levels of resolution of the time scale

One of the first questions that we considered in modeling the remediation process for the SICLUPS project was the length of the time scale. We found that the first length of time that we considered for the time scale, 6 years or one time segment, was too short a time to accomplish anything significant – it was doubtful if one could reasonably expect the complete remediation of even one site to be accomplished in this short a time. People at the Environmental Division of USACE spoke of a schedule of planned UXO remediations in the DERP-FUDS program as stretching out over several decades. It was clear to us from a consideration of estimated costs and current annual funding levels, that if annual funding levels do not increase substantially in the future, then the whole program of UXO remediations will indeed require several decades. So we decided that the planning period for the schedule to be determined by SICLUPS needs to be at least a few decades long.

The next question to consider was what length of time the basic unit of time for an IP or MIP formulation of the problem of finding the optimal or "best" schedule should represent. This is related to the question of what information one must have or assume about the lengths of time needed for the various tasks modeled, in formulating the IP or MIP model. Whatever length of time one chooses for the basic unit, *the model must know or make an assumption about the durations of these tasks in terms of a multiple of this unit*. For the problem we were dealing with in SICLUPS, we had no data on the basis of which to estimate these durations – it was a matter of making assumptions.

For the models for remediation of various types reviewed in Appendix C, the basic unit of time chosen was 1 year long. – therefore, these models need to make assumptions about the duration of each phase of remediation in years. We had to ask: for UXO remediation in the DERP-FUDS program, can we make a reasonable assumption about the length of each of the 3 phases of remediation in years?

The information we gathered in the data collection phase of this project, summarized in Appendix D, in particular, the information obtained by interviewing people at the Baltimore District Office of the North Atlantic Division of USACE, indicated that the length of time needed in actual practice for the study phase was highly variable and very difficult to predict. We were told that the length of time needed to actually carry out an Engineering Evaluation/Cost Analysis (EE/CA) was typically between 6 months and 2 years, but that because of the many steps involved in the study phase (of which the EE/CA is only one step) and the number of agencies whose participation in the study phase is essential, this phase could stretch over years. It became clear that if we made the basic time units in the MIP formulation 1 year long, then whatever assumption we made about the length of time needed for the study phase was likely to be incorrect in many cases.

It was clear, on the other hand, that *if the basic unit of time is to be made longer than 1 year, then the uncertainty in the length of time needed for the study phase will not be so large compared to the length of this unit.* We decided to make the basic unit of a time in the MIP formulation equal to one 6-year time interval, called a *time segment*. The result was that, instead of having to decide what specific year the study phase would begin, the model would only have to decide during which of 6 time segments this phase would begin.

Having the basic unit of time for the MIP formulation equal to 6 years instead of 1 year provided a second advantage: a savings in computing time. Assuming a 36-year planning period, we can compare the number of binary variables needed for the case of 36 1-year time segments versus the number needed for 6 6-year time segments. For SICLUPS, there are two arrays of binary variables with of $s \times p \times t$ variables in each array, where s is the number of sites, p is the number of phases, and t is the number of time segments. For the full-sized SICLUPS model, there are 126 sites, so if we have 6 time segments, each representing a 6-year time interval, then we have s=126, p=3, and t=6, giving a total of 4536 binary variables. By contrast, if for the same 36-year planning period we have 36 time segments, each representing a 1-year time interval, then we have t=36, giving 27,216 binary variables. The model with 4536 binary variables was shown to be solvable, usually in under 20 hours, for many combinations of parameter values, as reported in Appendix G. On the other hand, a model of with over 27,000 binary variables would usually not be practical to solve on the same hardware.

Result of having two levels of resolution of the time scale: a two-step process in determining the year-by-year schedule

For the reasons given in the previous section of this Appendix, we decided to let the time slots for the MIP models in SICLUPS be 6-year time segments. But, since the Army operates on annual budgets, what the Army needs for planning purposes is a schedule at the year-by-year level. The result is a two-step process: first to determine the schedule at the time segment level, then to refine the schedule at the time segment level to a year-by-year schedule.

A very straightforward way to determine this refinement is described in Chapter 6. This method works quite generally, the only restriction is that all of the annual budgets for the years in the same time segment must be equal. A consequence of this way to do the refinement is that funding for the more expensive tasks, namely phases 1 and 3 of remediation, tends to be fragmented – it is often spread out over 5 or 6 years.

An alternative option for determining schedules at the year-by-year level

Another method for determining a schedule at the year-by-year level from a schedule at the time segment level, that works in some cases, is described in this Appendix. This method gives a schedule for which funding for phase 1 is less fragmented – instead of being spread over 5 or 6 years it is covered in 2 years. In fact, when successful, this method gives a schedule having the following 2 properties:

(1) *Funding for phase 1* for each site remediated *is allocated in two consecutive years, with an allocation for ½ of the cost of this task in each of the two years*,
(2) For each site remediated, there is a gap of at least one year between the end of the 2nd year of funding for phase 1 and the beginning of funding for phase 2.

A possible reason that property **(2)** may be considered desirable was given in Appendix E.

An unfortunate complication is that it cannot be said that the method always determines precisely a refinement of the given schedule at the time segment level to a schedule at the year-by-year level. This is because, in some cases, it is necessary to first revise the schedule at the

time segment level. Then this revised schedule at the time segment level is refined to the year-by-year level.

The application of the method to the specific schedule at the time segment level described in Chapters 4 and 5 will now be described. References for the mathematical notation and terminology used here and elsewhere in this report are given in the Bibliography.

The schedule at the time segment level output by the SICLUPS optimization program for the specific case studied in Section 5.2 is shown in Figures 8 and 9 in Chapter 5. Let this schedule be called the *original schedule at the time segment level*. For each time segment, this schedule gives a list of sites for which tasks will be done. For each of these sites, this task is either one or two phases of remediation; if it is two phases, then it is either phases 1 and 2 or phases 2 and 3. Let

S_i = the set of sites for which phase i is to be done in the first time segment, according to the original schedule at the time segment level, i= 1, 2.

Then the set of sites for which the original schedule at the time segment level states that both phases 1 and 2 are to be done in the first time segment is $S_1 \cap S_2$. From Figures 8 and 9, one can read off the members of $S_1 \cap S_2$: they are the sites listed in the 1st and 2nd columns of Figure 8 together with the following 3 sites listed in the 3rd column of Figure 8:

F0287a, C0710, and C7044.

The basic idea for scheduling phase 1 for the sites in $S_1 \cap S_2$ is that phase 1 should be done early enough in the time segment so that there is still time to do phase 2 later in the time segment. To see whether this is possible, one must compare costs to budgets. The annual budget for each year in the Time segment is a number, bud. The sum of the costs of phase 1 for the sites listed in the 1st column of Figure 8 is slightly under 2*bud. Likewise, the sum of the costs of phase 1 for the sites listed in the 2nd column of Figure 8 is slightly under 2*bud. Let

T_i = the set of sites listed in column i of Figure 8, i = 1, 2.

Then the two statements above about costs can be written in mathematical notation as follows:

(A) Σ { cost of phase 1 for site s: $s \in T_1$ } $\leq$ 2 * bud

(B) Σ { cost of phase 1 for site s: $s \in T_2$ } $\leq$ 2 * bud.

Moreover, we note that $T_1 \cup T_2 \subset S_1 \cap S_2$ and, in fact, from the above statement about what sites are members of $S_1 \cap S_2$, it follows that

$$S_1 \cap S_2 = T_1 \cup T_2 \cup \{ \text{F0287a, C0710, C7044} \}.$$

Costs also satisfy the following condition:

(C) for every site s, cost of phase 2 $\leq$ ½ cost of phase 1.

For sites in $T_1 \cup T_2$, there is no difficulty in deciding in what year to fund phases 1 and 2:

for each site in T_1,
let funds covering ½ the cost of phase 1 be allocated in the 1st year,
let funds covering ½ the cost of phase 1 be allocated in the 2nd year, and
let funds covering the full cost of phase 2 be allocated in the 5th year.

(*)

for each site in T_2,
let funds covering ½ the cost of phase 1 be allocated in the 3rd year,
let funds covering ½ the cost of phase 1 be allocated in the 4th year, and
let funds covering the full cost of phase 2 be allocated in the 6th year.

With this method of allocation, it follows from conditions (A), (B), and (C) that the totals of all allocations are within budget. Moreover, the allocations satisfy properties **(1)** and **(2)** above.

Thus, for 35 of the 38 sites in $S_1 \cap S_2$, there is a satisfactory way to determine in what specific years within the first time segment funding for phases 1 and 2 will be allocated. Unfortunately, this solution *does not extend* to the remaining 3 sites in $S_1 \cap S_2$. After funds from the budgets for the first 2 years have been committed to sites in T_1, there is very little remaining. Likewise, after funds from the budgets for the 3rd and 4th years have been committed to sites in T_2, there is very little remaining. The total amount not yet committed from the budgets of the 1st 4 years is far less than the cost of phase 1 for the remaining 3 sites. For these 3 sites, funding for phase 1 can committed from the 5th and 6th years, but then there will be no time remaining in the time segment to fund phase 2.

One solution to this difficulty involves revising the original schedule at the time segment level – that is, getting another schedule at the Time segment level, before refining any part of the schedule to the year-by-year level. If one has a *revised schedule at the time segment level*, let

$S^R{}_i$ = the set of sites for which phase i is to be done in the first time segment,
according to the revised schedule at the time segment level, i= 1, 2.

Here, the superscript “R” indicates that the set is defined in terms of the revised schedule. What is desirable is to find a revised schedule with the property that $T_1 \cup T_2 = S^R{}_1 \cap S^R{}_2$, so as to avoid the difficulty that was encountered with the original schedule. This involves revising the original schedule so that phase 2 for the remaining 3 sites F0287a, C0710, and C7044 are scheduled for time segments later than the first time segment.

This type of revision is possible. It is done as follows: From the first (human-readable) output file of the optimization program, we observe that the original schedule at the time segment level states that, of the 126 sites in the model, all 3 phases of remediation are to be carried out for 83 of the sites, and 1 or 2 phases of remediation are to be carried out for each of 4 other sites. Figures 8 and 9 together show the names of the 83 sites that are completely remediated, together with the time segment during which each of the 3 phases of each of these sites is to be carried out, according to this original schedule. The partial remediations are as follows:

for site C0805, phase 1 is carried out during time segment #5;
for site C7062, phase 1 is carried out during time segment #5;

for site C0190, phase 1 is carried out during time segment #1;
for site C0258, phases 1 and 2 are carried out during time segment #5.

The *revised schedule at the time segment level* is constructed as follows:

(1) delete all 5 tasks in the partial remediations, freeing funds during time segments #1 and #5 ;
(2) for each of sites C0710 and C7044, reschedule phases 2 and 3 to time segment #5, using the funds in the budget for time segment #5 which were freed via step (1);
(3) for site F0287a, note that according to the original schedule at the time segment level funds to cover the cost of phase 3 have been allocated in time segment #4. Revise this as follows: In time segment #4, reduce the amount allocated for phase 3 by the amount needed for phase 2, and complete phase 2 and the fraction of phase 3 whose cost is covered by the remainder. Then in time segment #5, complete phase 3 with the remainder of the funds which were freed via step (1).

This completes the specification of the revised schedule at the time segment level. Note that among the 83 sites to be completely remediated, the schedule has been revised for only the 3 sites F0287a, C0710, and C7044.

Now for the revised schedule at the time segment level, S^R_1 is precisely the set of 46 sites listed in Figure 8, and S^R_2 is precisely the set of the 35 sites listed in the first two columns of Figure 8. That is, the revised schedule requires that phase 1 be done in the first time segment for all 46 of these sites and that phase 2 be done in the first time segment only for 35 of them. We have the desired condition

$$T_1 \cup T_2 = S^R_1 \cap S^R_2.$$

The preceding discussion shows that from this condition and conditions (A), (B), and (C) above, it follows that for every site in $S^R_1 \cap S^R_2$, phase 1 can be funded from the budgets of the first 4 years of the time segment and phase 2 can be funded from the budgets of the last 2 years of the time segment. From Figure 9, which describes the original schedule at the time segment level, and from the above description of the revised schedule at the time segment level, it is clear that the only tasks slated by the revised schedule to be done in the first time segment are the phase 1 and phase 2 tasks described above. So this completes the refinement of the revised schedule at the time segment level to the year-by-year level for the first time segment.

For later time segments, the problem of refinement to the year-by-year level is similar, but is complicated by the fact that one can have a phase 2 task that is not linked to a phase 1 task, and the fact that there are phase 3 tasks. For each of the later time segments, however, the number of phase 1 tasks is small enough and their costs are small enough that funding for all of them can be obtained from the budgets of the first 4 years of the time segment. Some of these phase 1 tasks are linked to phase 2 tasks (i.e., phases 1 and 2 for a site are scheduled for the same time segment). These phase 2 tasks can be treated in the same way as was described for the first time segment above. The number of phase 2 tasks that are linked neither to phase 1 tasks nor to phase 3 tasks, called *isolated* phase 2 tasks, which are scheduled for any one time segment is

very limited – there are at most two such tasks per time segment. It is a simple matter of comparing costs and budgets to see that, in all cases, the costs of these are easily covered by the budgets of the 5th and 6th years of the time segment. Then there are (a) phase 3 tasks and (b) phase 2 tasks that are linked to phase 3 tasks (i.e., phases 2 and 3 for a site are scheduled for the same time segment). In the latter case, the phase 2 task and the phase 3 task linked to it are combined and considered as one task.

For each of the later time segments, funds from the budgets of the individual years of the time segment were committed first for phase 1 tasks in such a way as to satisfy condition **(1)**, then funds from the budgets of the individual years were committed for phase 2 tasks that were linked to phase 1 tasks in such a way as to satisfy condition **(2)**. The pattern thus far is similar to that for the first time segment, except that for later time segments, all of the phase 1 tasks are funded within the first 4 years, and not all of them are linked to phase 2 tasks. Then funds from either the 5th or the 6th year were committed to each isolated phase 2 task. Up to this point, the funding for each individual task comes either from one year's budget or from two consecutive years' budgets.

Finally, funds were allocated for the tasks in (a) and (b) above from the remaining funds in the 6 years of the time segment. For these tasks, however, the funding tended to be fragmented – there was no assurance that funding for one of these tasks would not be spread out over all 6 years of the time segment.

There is one further question, pertaining to condition **(2)**, whose answer may not be obvious to the reader. The condition (*) above for the first time segment and similar conditions for later time segments assure that condition **(2)** is satisfied for sites for which phases 1 and 2 are linked (i.e., for sites for which phases 1 and 2 are scheduled for the same time segment). But is **(2)** also satisfied for sites for which phases 1 and 2 are scheduled for different time segments? The affirmative answer is made easier to verify by the year-by-year scheduling of phase 1 tasks. In order for **(2)** to be violated, it would be necessary (a) to fund phase 1 in the 5th and 6th years of one time segment and (b) to begin funding of phase 2 in the next time segment. However, (a) occurs only for the first time segment, and here, only for the 11 sites in the 3rd column of Figure 8. For each of these 11 sites, the revised schedule at the time segment level has phase 2 occurring later than the 2nd time segment.

The revised schedule at the time segment level, with refinement to the year-by-year level shown only for the first time segment, is shown for Florida sites in Figure K-1.

Some concluding observations

A way to refine a schedule at the time segment level to a schedule at the year-by-year level, which is very simple and which works perfectly generally, was described in Chapter 5. Year-by-year schedules obtained via this method had the property that funding for phases 1 and 3 were often spread out over 5 or 6 years. This property may or may not be considered a disadvantage of the method.

A second way to do the refinement, which seems to be straightforward but not completely trivial to carry out and which works in some cases, was described above in terms of its application to a specific case. For this specific case, it was *not* found possible to apply this second method directly to the *original* schedule at the time segment level – that is, to the schedule which was output by the SICLUPS optimization program. But the method was

successfully applied to a revision of this schedule. The revision, which was at the time segment level, involved (1) deleting partial remediations of 4 sites and (2) altering the scheduling of phases 2 and 3 for 3 of the 83 sites remediated, but no other revisions. Year-by-year schedules obtained via this second method satisfied properties **(1)** and **(2)** above. Funding for phase 1 was less fragmented than with the first method, but funding for phase 3 was still fragmented.

We considered the question of for how large a subset of the set of all possible schedules at the time segment level this second method of refinement works, as well as some variants of this question, but the only definite answers we found were technically cumbersome. It appears that having the costs of both phase 1 and phase 3 consistently large compared to the costs of phase 2 and having phase 3 usually more expensive than phase 1 helped to make the method work. Limiting the number of sites for which phase 1 is scheduled for any one time segment also seems to help. In this respect, Type B models may have an advantage over Type A models.

Since the comparative costs of the different phases seem to be critical for making the second method of refinement work, and since there is so much uncertainty as to the accuracy of the cost estimates obtained thus far, we found it necessary to conclude that our data was not of sufficient quality to give us very much confidence in the value of doing further work on this method.

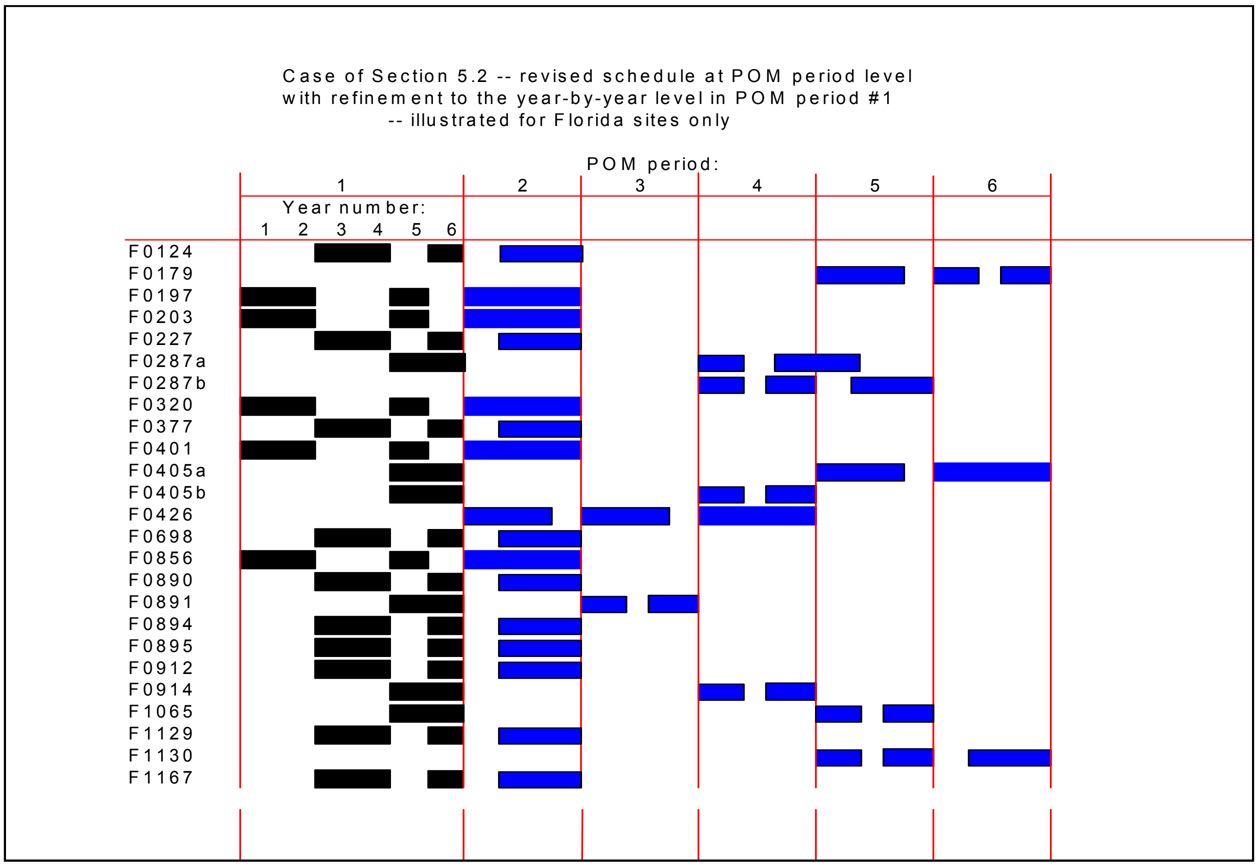

Figure K-1. Revised schedule at time segment level with refinement to the year-by-year level shown only for the first time segment – Florida sites only

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APPENDIX L ACREAGE AND RISK DATA

As complete data for the MIP model of SICLUPS as is consistent with our sponsor's instructions is given here. Our sponsor requested that we do not publish cost estimates. Acreage data was available for all 126 sites in the model, and RAC scores were available for 77 sites in the model. For the remaining 49 sites, the RAC score of 5 was assigned, as described in Section 3.2.

The same abbreviated names for the sites that were used in Chapter 5 are used here. Each name consists of (1) the initial of the state containing the site, followed by (2) the 4-digit sequence in the USACE-designated FUDS property number containing the site, followed in some cases by (3) a letter "a", "b", or "c". The procedure used to define specific sites was described in Section 3.2. For example, "F0377" is the abbreviated form of "I04FL0377" and "C0145" is the abbreviated form of "J09CA0145".

Figure L-1 gives acreage data for all 126 sites, which was supplied by AEC, and Figure L-2 gives the RAC data, which was supplied by USACE. In Figure L-1, the data is arranged with a row for each of the 3 main geographic areas and a column for each of 7 ranges of acreages. Each range is an interval of numbers of acres, except for the 5th range, which represents exactly 640 acres. For each site listed, other than those in the column labeled "640", the exact number of acres in the site is given in brackets after the name. In Figure L-2, the data is again arranged with a row for each of the 3 main geographic areas and a column for each of 5 RAC scores.

Area:	Range of acreages						
	1--10	11--100	101--400	401--639	640	641--2499	>=2500
Florida		F0124 [11] F0227 [11] F0401 [36] F0895 [40]	F0320 [150] F0377 [260] F0890 [320] F0912 [219] F1065 [121] F1167 [200]	F0405b [602] F0856 [535]	F0203 F0891 F0894 F0914	F0197 [906] F0287a [2259] F0405a [1760] F0426 [650] F0698 [650] F0832 [1782] F1129 [1000]	F0179 [3080] F0287a [3245] F1130 [5890]
SF+SAC Districts	C3107 [6] C7062 [2] C7293 [5]	C0094 [40] C0805 [29] C0877 [40] C0950 [12]	C0781 [270] C1039 [144] C7297 [200] C7466 [140]	C0064 [427] C7287 [510]	C1074 C7290	C0876 [653] C7019 [1040] C7059 [913] C7478 [642]	C7288 [3185]
Los Angeles District	C0180 [1] C0181 [1] C0182 [1] C0184 [1] C0186 [1] C0187 [1] C0189 [1] C0190 [2] C0191 [1] C0197 [1] C0214 [2] C0215 [2] C1110 [2] C7347 [10]	C0150 [33] C0188 [38] C0198 [20] C7153 [19] C7236 [24] C0156 [90] C7044 [100]	C0273 [316] C0274 [177] C0677 [343] C0679 [170] C0681 [270] C0685 [360] C0689 [357] C1120 [142] C7074 [216] C7115 [369] C0147 [400] C0676 [400] C0690 [400]	C0146 [480] C0170 [460] C0587 [637] C0675 [560] C1130 [510] C7129 [558] C7315 [500]	C0174 C0177 C0185 C0255 C0258 C0259 C0672 C0680 C0686 C0688 C0692 C0696 C7309	C0045 [658] C0145 [960] C0153 [649] C0172 [661] C0173 [677] C0209 [1800] C0278b [1280] C0284b [2397] C0674 [1540] C0691 [1490] C0693 [645] C0695 [2240] C1069 [649] C7313 [1200]	C0254 [2560] C0256 [2560] C0257 [2540] C0261 [2560] C0262 [2560] C7310 [2560] C0278a [3850] C0278c [19900] C0284a [6877] C0348 [3310] C0710 [28005] C7329 [4911]

Figure L-1. Acreages of all 126 sites in full-sized SICLUPS models

Area:	RAC score 1	2	3	4	5
Florida (26/26)	F0124 F0405a F0405b F0698 F0891	F0197 F0401 F0832 F0890	F0287a F0287b F0320 F0377 F0426 F0856 F0912 F0914	F0179 F0203 F0894 F0895 F1129 F1167	F0227 F1065 F1130
SF+SAC Districts (3/20)			C0064	C0876 C0950	
Los Angeles District (48/80)		C0170 C0209 C0278a C0278b C0278c C0284a C0284b C7044	C0147 C0150 C0172 C0174 C0177 C0180 C0181 C0188 C0255 C0259 C0273 C0348 C0587 C0675 C0692 C0693 C1130	C0145 C0146 C0153 C0156 C0182 C0184 C0185 C0186 C0187 C0189 C0197 C0254 C0256 C0257 C0258 C0261 C0262 C0274 C0680 C0681 C0695 C0710	C0679

Figure L-2. RAC scores for 77 sites in SICLUPS models

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